Exercise and Cognitive Function

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Preface

For more years than we care to remember, we have been studying the effect of exercise on cognitive function. To us it is a fascinating subject and we are delighted to have seen this field of research blossom in recent years. The main purpose of this book is to stimulate further research and scholarship in this area. Not only do we need more research but we also require the development of sound theoretical frameworks. Some of you reading this book will already have been involved in research and/or theorising. However, many will not, but we hope that you will join us. We should note here that the study of exercise and cognitive function also helps us to understand how other stressors affect cognition and, indeed, provides useful information for anyone interested in how the brain works.

As well as encouraging more research, we are keen to develop inter-disciplinary work. We believe that this is the only way in which we will increase our knowledge of the exercise-cognition interaction. In this book we have drawn together researchers from differing disciplines, e.g. cognitive psychology, cognitive neuroscience, exercise biochemistry, psychophysiology. In Part 1 we examine theoretical and methodological aspects. Michel Audiffren begins with an interesting overview of how theory has developed before outlining the input that we can receive from cognitive-energetic models of the arousal–cognition interaction. In Chapter 2 Terry McMorris takes a neuroendocrinological approach, while in Chapter 3 Arne Dietrich puts forward his somewhat controversial theory of transient hypofrontality. Whether you agree with Arne or not, this is a very interesting read and it raises some important factors. In the last chapter in this section, Phillip Tomporowski discusses the many methodological issues involved in undertaking such research. Phillip's great experience in this field makes this chapter a 'must' for anyone who wishes to undertake research in this area.

Parts 2 and 3 examine research findings with Part Two examining research using acute exercise and Part 3 looking at chronic exercise. In Part 3 Terry McMorris examines research into the effect of exercise and dehydration (Chapter 5) and exercise and performance in team games (Chapter 9). Both are areas of limited research but ones which have practical importance. In Chapter 6 Adam Cunliffe and Gulshanara Begum examine another under-researched area, the interaction between exercise, nutrition and cognition and they raise some very interesting and practical issues. In Chapter 7, Karen Davranche and Michel Audiffren provide an overview of some of the research that they have undertaken to examine whether exercise affects

motor or premotor aspects of reaction time tasks. The results of their studies, so far, suggest that this is a fruitful area of research. In Chapter 8, Charles Hillman, Matthew Pontifex and Jason Themanson from the University of Illinois at Urbana-Champaign examine research that has been carried out using psychophysiological techniques. The Urbana-Champaign group have provided some very exciting research in this area. In the final chapter, Niels Secher, Thomas Seifert, Henning Nielsen and Bjørn Quistorff from the University of Copenahgen provide the very latest on the processes affecting blood glucose and brain metabolism during exercise. This chapter provides us with invaluable information concerning the underlying processes that might affect the exercise–cognition interaction.

The first chapter of Part 3, by Caterina Pesce, actually straddles both acute and chronic exercise and, as Caterina says, we researchers should probably take each into account rather than just focusing on the one. In Chapter 12, Jennifer Etnier provides a fascinating review of the vast amount of work that has examined chronic exercise and cognition in the elderly. While in Chapter 13, Catherine Davis and Kate Lambourne examine the other end of the age spectrum looking at children. In particular they report on a fascinating study undertaken in Georgia, USA. The final two chapters examine exercise and disabilities. In Chapter 14, James Zagrodnik and Michael Horvat look at research with children, while in Chapter 15 Laura Eggermont and Erik Scherder examine exercise and brain diseases. The potential for exercise to be used to prevent diseases such as Alzheimer's and Parkinson's is a very exciting one. In Part 4 we present an overview of the book and raise some topics for future research.

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We would like to thank, very much, all of the contributors to this book, who have taken time out from very busy schedules to provide us with their expertise. Also we give great thanks to the staff at Wiley-Blackwell in Chichester, especially Celia Carden, for all their help. We would also like to thank the many individuals from all over the World who have given of their time to be subjects in research. It can be very hard and even when they are paid it is not enough.

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PART 1

THEORETICAL AND METHODOLOGICAL ISSUES

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1

Acute exercise and psychological functions: a cognitive-energetic approach

Michel Audiffren

Feelings of efficiency or inefficiency are often reported by people practising a mental task during or following a physical activity. For instance, athletes know from experience that performing a warm-up exercise improves their reactivity to a start signal; soldiers carrying heavy loads complain about the debilitating effect of central fatigue on decision making while walking long distances; and the elderly are aware that regular physical activity improves mental health and autonomy. In spite of these popular and professional beliefs, the interactions between the physiological changes, induced by exercise and the psychological functions potentially affected by these changes were, and still are, the object of an extended debate. Today, a large number of scientific studies support a positive effect of exercise on psychological functions (for recent narrative and meta-analysis reviews see Colcombe and Kramer, 2003; Etnier *et al.*, 2006; McMorris and Graydon, 2000; Tomporowski, 2003b). The purpose of this chapter is to present different theories and methods drawn from cognitive and energetic approaches that explain the effects of exercise on psychological processes. In addition, we will attempt to determine the location of these effects in the cognitive-energetic architecture of the information processing system.

The chapter is organized as follows. The first section will be devoted to the proposal of common taxonomies for the effects of exercise on psychological and physiological variables. These taxonomies will guide the choice of adequate physiological interventions, cognitive tasks and theories or models, which can explain the different effects of exercise on psychological processes. In the second section, the cognitive psychology approach and the information processing paradigm will be briefly presented. This approach provides very powerful methods that allow the study of the effect of exercise on psychological functions. The energetic approach will be

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assessed in the third section, as it supplies a very useful theoretical framework from which to understand the acute effects of exercise on cognition. In the fourth section, four cognitive-energetic models explaining the facilitating and debilitating effects of acute exercise on information processing will be proposed. The fifth section will present six methods from cognitive psychology that explain the localization of the effects of exercise in the architecture of cognitive-energetic systems. Finally, in the sixth section, some limits of the cognitive-energetic approach will be discussed and complementary approaches that could give additional information on the mechanisms underlying the effects of exercise on cognition will be suggested.

1.1 Varieties of exercise effects on psychological variables

The literature on the effects of exercise on psychological functions is abundant. From 1960, several hundred experiments have been conducted throughout the world on this topic. Four kinds of results are generally reported: (1) an improvement in psychological functions; (2) an impairment of psychological functions; (3) a change in strategy to maintain psychological test performance; and (4) no effects on psychological functions. The fourth category is problematic because researchers cannot distinguish between two possible reasons for the failure: (1) there is no effect of exercise on psychological functions in the real world or (2) the methodology used in the experiment was not appropriate to show a significant effect of exercise on psychological functions. The three other categories of results are the most interesting because they lead to new questions: (1) what are the adequate conditions to observe these phenomena (intensity and duration of exercise, time of observation during or after exercise, age and cardiovascular fitness of participants, etc.); (2) which physiological mechanisms explain these positive or negative effects on psychological processes; and (3) which psychological processes are affected by these mechanisms. The aim of this first section is to propose taxonomies for the interaction between exercise and cognitive tasks, which can help scientists to conceptualize future research on the topic.

Aerobic versus anaerobic exercise

Studies that assessed the effects of exercise on psychological functions have used a large variety of exercise protocols (see Tomporowski and Ellis, 1986, for a narrative review). Physical exercises performed by the participants can be classified according to their mode of progress (constant or incremental load), their intensity and duration, and the two general metabolic pathways that supply the energy to the muscle (aerobic and anaerobic). According to the review by Tomporowski and Ellis, four categories of exercises can be distinguished (see Table 1.1).

The intensity of exercise is generally defined according to the capabilities of the participants. Different indices have been used by researchers to determine the same relative intensity of exercise for all participants: for instance, the percentage of

Table 1.1 Taxonomy of physical exercises as a function of duration and intensity of the physiological intervention.

Mode of exercise	Duration	Intensity	Metabolic pathway	Example
Constant-load exercise	Very brief <3 min	Supra-maximal >100% VO_2max	Anaerobic	Handgrip at maximal force
Ramp incremental exercise	Moderate 10 to 25 min	Up to maximal Up to 100% VO_2max	Aerobic and Anaerobic	VO_2max test
Constant-load exercise	Short to moderate 5 to 60 min	Sub-maximal 30 to 80% VO_2max	Aerobic	Walking on a treadmill
Constant-load exercise	Long > 60 min	Sub-maximal 30 to 80% VO_2max	Aerobic	Marathon race

maximal oxygen uptake (e.g. Delignières, Brisswalter and Legros, 1994; Travlos and Marisi, 1996), the percentage of maximal power output (e.g. Arcelin, Delignières and Brisswalter, 1998; Hogervorst *et al.*, 1996; McMorris and Graydon, 1996a; Paas and Adam, 1991), the percentage of ventilatory threshold (e.g. Davranche *et al.*, 2005a, Davranche, Audiffren and Denjean, 2006a), the percentage of lactate threshold (Chmura *et al.*, 1998; Kashihara and Nakahara, 2005), the percentage of maximal heart rate (e.g. McGlynn *et al.*, 1979), the percentage of heart rate reserve (e.g. Pesce, Casella and Capranica, 2004), or the rating of perceived exertion (e.g. Kamijo *et al.*, 2004b). In Table 1.1, the intensity of exercise is expressed in percentage of maximal volume of oxygen uptake (%VO_2max), a function of the cardiorespiratory system reflecting the total amount of oxygen that the individual can utilize. This index is commonly used in exercise physiology and exercise psychology.

Physiological mechanisms providing energy to the muscle and physiological states induced by exercise vary considerably from one category of exercise to the other. Very brief and intense exercise, described in the first line of Table 1.1, mainly involves the anaerobic metabolism. It may be localized, such as a handgrip at maximal force, or involve the whole body, such as in the 100 m sprint. The anaerobic metabolism does not require oxygen and yields small quantities of adenosine 5′-triphosphate (ATP) per mole of glucose or muscle glycogen. Three separate anaerobic mechanisms, initiated in parallel but varying markedly in duration, provide ATP to the muscle following the initiation of this type of exercise (Ward-Smith, 1999): (1) a small quantity of endogenous ATP molecules stored in muscle, which are depleted in approximately 5 s; (2) the breakdown of intramuscular phosphocreatine (PCr) that contributes to the production of ATP and lasts approximately 10 s; and (3) the oxygen-independent glycolysis that supplies predominantly the ATP from 10 to 100 s. Blood lactate and H^+ ions are the end products that are released into the blood by this oxygen-independent glycolysis. The availability of phosphagens (ATP and PCr), and

blood acidosis are generally accepted to be two of the most likely limitations to anaerobic muscle performance. Very brief and intense exercise presents two problems for studying the effects of exercise on cognition. On the one hand, due to the short duration of the exercise, the number of trials recorded during the exercise for the cognitive task is necessarily small. On the other hand, peripheral fatigue mechanisms take place during this category of exercise. Studies not concerned with these peripheral fatigue phenomena should choose one of the other categories of exercise.

Graded exercise, described in the second line of Table 1.1, in which exercise intensity is progressively increased from light intensity to exhaustion, involves anaerobic as well as aerobic mechanisms. When exercise is sustained beyond 100 s, aerobic metabolism, which requires oxygen and yields large quantities of ATP per mole of glucose, progressively replaces anaerobic metabolism as the main source of energy. In a graded exercise, the aerobic mechanism provides the larger part of the energy until the anaerobic lactate threshold is reached. Anaerobic lactate threshold represents the critical point at which metabolic modifications bring about the energy-demand transition from aerobic to anaerobic exercise. Incremental exercise until exhaustion presents a serious limit for studying the effect of exercise on cognition because the participants' physiological state changes throughout the exercise. During the first minutes of the exercise, the energy is mainly supplied by aerobic mechanisms, and there is no fatigue nor any real mental effort required to sustain the relatively low intensity of exercise. By contrast, during the last minutes of this kind of exercise, the energy is mainly supplied by anaerobic glycolysis, participants generally feel peripheral fatigue and a high level of mental effort is required to continue the exercise.

Aerobic exercise of moderate duration, described in the third line of Table 1.1, seems to be the most interesting category of exercise to study the positive effect of exercise on cognition. There are three main reasons for this: (1) participants perform at steady-state throughout the entire exercise session and aerobic mechanisms are the main source of energy soon after the beginning and until the end of exercise; (2) a cognitive task involving a large number of trials can be performed simultaneously to the exercise; and (3) central as well as peripheral fatigue phenomena are limited, which is in contrast to the three other categories of exercise. Finally, aerobic exercise of long duration, described in the fourth line of Table 1.1, is more interesting for studying the effects of central fatigue on cognition. The last two categories of exercise generally require whole-body activation.

Acute versus chronic exercise

There is another very important distinction concerning the protocols used to study the effects of exercise on cognition. Both acute and chronic exercise have been extensively used, but they must be distinguished because they induce different changes in the organism (see Table 1.2). While acute exercise concerns itself with a single bout of exercise, chronic exercise concerns itself with the repetition of bouts of

Table 1.2 Taxonomy of physical exercises as a function of physiological changes they induce.

Type of effect	Mode of exercise	Type of physiological change	Type of brain mechanism underpinning the effect
Acute effect	Single bout of exercise	Transient	Modulation of the activity of a neural network
Chronic effect	Regular exercise	Durable	Anatomical changes in the brain structure

exercise over time, lasting from weeks to years (Audiffren *et al.*, 2007a). The behavioural and psychological changes induced by a single bout of exercise generally appear quite rapidly after the beginning of exercise (seconds to minutes) and disappear relatively quickly after its cessation (minutes to hours). Neurophysiological changes, which underlie the transitory behavioural and psychological changes induced by exercise, can be viewed as a transient modulation of the activity of the neural networks involved in the cognitive task or the mental state of interest. In contrast, chronic effects of exercise reflect structural and durable changes in the organism, like angiogenesis (e.g. Swain *et al.*, 2003), synaptogenesis (e.g. Chu and Jones, 2000) or neurogenesis (e.g. van Praag *et al.*, 1999).

The behavioural and psychological changes induced by the regular practice of a physical activity typically appear a few weeks after the beginning of the exercise programme and can be maintained several weeks after its termination. Neurophysiological changes underlying stable behavioural and psychological changes induced by exercise can be viewed as durable anatomical changes in the brain structure at different possible levels (e.g. neuroreceptor, synapse, neuron, neural network, brain structure). In this chapter, we will focus on theories and models which can explain the acute effects of exercise on cognitive processes.

Bottom-up versus top-down processes

Psychometric tasks used to examine the acute effects of exercise on psychological processes involve a large variety of sensorimotor and cognitive processes. According to Paillard (1986, 2005), it is useful to distinguish these two levels of information processing (see Figure 1.1). On the one hand, the sensorimotor level can be conceived as an interface between the brain and its environment. Ascending information gathered by sensory organs for further processing through attentional control and descending commands for self-generated movements require this sensorimotor interface. The sensorimotor level is mainly genetically pre-wired and supplies vital functions such as stretch reflex and orienting reaction. On the other hand, the cognitive level is underpinned by an apparatus endowed with the whole resources of neocortical and limbic structures and able to process a large variety of mental states that characterize higher brain functions. The sensorimotor level mainly functions in a reactive way, but possesses its own adaptive loops, whereas the

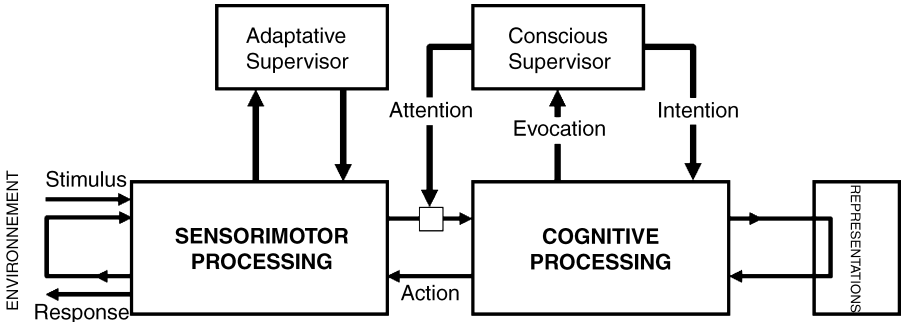

Figure 1.1 Sensorimotor and cognitive levels of information processing. (Modified from Paillard, 1986, 2005.)

cognitive level anticipates events and functions in a predictive way on the basis of abstract representations of internal and external worlds stored in long-term memory.

Each of these two levels of information processing can be separated into different modules, stages or functions (Fodor, 1983; Sternberg, 2001). For instance, information processing may be separated into sensory, perceptual, decisional and motor stages (Sanders, 1983), while executive processes can be separated into three basic functions, inhibiting pre-potent responses, updating working memory and shifting between tasks or rules (Miyake *et al.*, 2000). Recent empirical data suggest that steady-state aerobic exercise does not affect all these stages and functions, but influences some of them in different ways (Audiffren, Tomporowski and Zagrodnik, 2008; Davranche *et al.*, 2005a, 2006b; Dietrich and Sparling, 2004). Bottom-up stimulus-driven processes (see left column of Table 1.3) would be improved by acute aerobic exercise, whereas top-down effortful processes (see right column of Table 1.3) would be impaired. This idea of a bi-directional effect of arousing stimulation on information processing is not new, but

Table 1.3 The hypothetical bidirectional effect of acute bout of steady-state aerobic exercise on cognitive processes.

Improvement of performance	Impairment of performance
Bottom-up	Top-down
Stimulus-driven	Goal-driven
Automatic	Effortful
Implicit	Explicit
Unconscious	Conscious

Note: When participants perform a cognitive task while exercising, performance of the cognitive task may be either improved or impaired. Tasks which tap processes showing several characteristics described in the right column tend to be improved, whereas tasks which involve processes presenting several characteristics described in the left column tend to be impaired (see text for more explanations). Each line describes a bi-dimensional continuum (e.g. Automatic–Effortful). There is no dimensional overlap between the five bi-dimensional continua. For instance, a top-down process may be totally unconscious, or a stimulus-driven process may require allocation of effort.

similar to the distinction between sustained information processes and short-term memory processes made by Humphreys and Revelle (1984) and tested in exercise protocols by Paas and Adam, and their co-workers (Adam *et al.*, 1997; Paas and Adam, 1991). Currently, there is no general theory providing a synthesis for all these new data, approaches and hypotheses concerning the effects of acute bouts of aerobic exercise on cognitive processes. Several chapters of this book lay the foundation for a new theoretical framework explaining the multiple interactions between acute exercise and cognition.

The assessment of the effects of exercise on cognition should include: (1) the choice of an adequate physiological intervention; (2) the selection of tasks according to the sensorimotor and cognitive processes they involve; and (3) the separation of cognitive stages and functions within the same task. Different methods worked out by cognitive psychologists and cognitive neuroscientists in order to separate sensorimotor stages and cognitive functions will be presented later.

1.2 The cognitive psychology approach

Cognitive psychology emerged in the middle of the twentieth century. This branch of psychology is based on the theoretical framework of the cognitive sciences (i.e. artificial intelligence, mathematics, linguistics, philosophy, neurosciences and psychology). Therefore, mathematics inspired three main ideas of cognitive psychology (Andler, 1986). The first idea considers the language of the mind as a formal system. A formal system is a set of symbols that can be combined according to rules based on the shape of the symbols. Puzzles, alphabets and languages are all examples of formal systems. The mind uses these symbols to generate thoughts. The second idea considers the mind as a computing machine. The first universal computing machine was conceptualized by the English mathematician Alan Turing. A Turing machine is composed of an input/output system that can write and read a finite set of symbols, and of a memory system that can assume a finite set of states. According to Turing (1950), a machine could operate in the same way as the human mind. Thoughts, then, would simply be a combination of symbols. The third idea considers the mind as a channel of communication conveying information. This idea was inspired by the seminal paper entitled '*The Mathematical Theory of Communication*' published by Claude Shannon in 1948. In this article, Shannon proposed a linear system of information transmission and provided a quantitative definition of information, or uncertainty, measured in bits. Different laws predicting human behaviour, like Hick's law (Hick, 1952) or Fitts' law (Fitts, 1954), were formalized by cognitive psychologists thanks to Shannon's theory of communication. The quantitative definition of information is very useful to objectively determine the complexity of the task or the uncertainty the participants have to cope with.

These three main ideas led cognitive psychologists to conceptualize the information-processing paradigm. The term 'paradigm' is used here in the sense of Kuhn (1962), that

is to say, the ideas, theories, methods, techniques and applications shared by a community of researchers to solve important scientific problems. Typically, a paradigm is first established by the publication of a revolutionary book or paper that sets out scientific problems and possible solutions. This chapter focuses on the information-processing paradigm because the larger part of studies interested in the effect of exercise on psychological functions used this specific approach.

Five basic assumptions underlie the information-processing paradigm and are shared by the community of cognitive psychologists: (1) there are mental states involved in mental processes; (2) mental states possess physical existence as physical states (i.e. they result from the electrochemical activity of neurons); (3) mental states cannot be reduced to physical states; (4) mental states take place in a computing system like the Turing machine (i.e. the mind is a symbol-processing system); and (5) a mental state corresponds to a representation and a mental process operates transformations of representations. One of the central concerns of cognitive psychology is to study these representations and mental processes. Because these objects are not directly observable, cognitive psychologists developed methods to infer some of their characteristics from the measurement of different variables, such as reaction time, and correct and incorrect response rates.

Behavioural psychologists assumed that scientific psychology must be based on directly observable facts such as stimuli and responses without any reference to hypothetical inner states. By contrast, cognitive psychologists are interested by states and processes that take place between sensory inputs and motor outputs of the information-processing system. These hypothetical inner states and processes are considered as intermediary or latent variables; intermediary because they take place between stimuli and responses, and latent because they are not directly observable, but inferred from variations of dependent variables.

Typical topics of cognitive psychology include attention, pattern recognition, memory, motor control, reasoning, problem-solving, language, decision-making, learning and, more recently, executive functions. Typical goals of cognitive psychology are to formulate general principles and laws concerning cognitive processes that are true for everyone; to separate the human information processing system into components; to identify the nature and duration of the component processes involved in the performance of a cognitive task; and to describe the architecture of the cognitive system in order to explain human mental performances in a large variety of situations. The information-processing paradigm was still dominant and considered by the majority of cognitive psychologists as the appropriate way to study human cognition in the last decades of the twentieth century (Eysenck and Keane, 1990). Today, thanks to the technological progresses in different branches of neurosciences, such as brain imagery, it becomes necessary to shift from a 'pure' cognitive psychology approach to a cognitive neuroscience approach to have a better understanding of cognitive functions.

Since the beginning of cognitive psychology, two major conceptual frameworks of human information processing were in competition: the resource-driven models and the data-driven models (Rabbitt, 1979; Sanders, 1983). Generally speaking,

resource-driven models consider that performance of the human operator in a task requiring processing of information depends on three things: (1) the amount of available resources; (2) the amount of resources required to perform the task; and (3) the amount of resources actually allocated to the different processes involved in the task. Resources can be defined as energizing forces necessary to perform tasks (Gopher and Donchin, 1986). Human information processing and digital computers of the 1960s were conceived as limited capacity systems (Sanders, 1997), that is to say, systems which possess a limited amount of resources. In contrast, data-driven models consider that performance depends on the quality of the processing realized by a sequence of stages that transform input representations into output representations. A processing stage refers to an aggregate of computational processes that participate in the same mental operation, such as feature extraction or response selection (Gopher and Donchin, 1986). Pure data-driven models inspired by the computer metaphor do not explain variability of performance under different environmental or internal states of the organism (e.g. heat, stressful noise, emotion, effects of drugs, fatigue and arousal induced by exercise) (Hockey, Coles and Gaillard, 1986). In order to explain such variability in the information-processing system, it becomes necessary to combine resource- and data-driven approaches. The resource-driven approach shares several ideas with the energetic approach presented in the next section. For instance, the concept of resources is closely related to the concept of arousal.

Cognitive psychologists developed ingenious methods to infer mental processes, which take place between stimuli and responses, and the make-up of the architecture of the information-processing system (e.g. Sternberg's additive factors method, 1969a). Several of these methods can be also used to determine the locus of influence of aerobic exercise within the information-processing architecture and will be presented later in this chapter. The architecture of the information-processing system has been described in different models (e.g. Sanders' discrete/serial information processing model, Sanders, 1990). In the fourth section of this chapter, cognitive energetic models that synthesize the theoretical frameworks from cognitive and energetic approaches will be presented. They provide a very useful theoretical framework, which explains the different effects of exercise on cognitive processes.

1.3 The energetic approach

The energetic approach is concerned with the intensive or energizing aspects of behaviour as opposed to its directional or semantic aspects. Concepts such as arousal and activation were associated early with energy mobilization or energy release within the organism (Duffy, 1962) and their relation to performance can be traced to the earliest decades of experimental psychology and neurophysiology. For instance, Yerkes and Dodson (1908) observed an inverted-U shaped function of efficiency depending upon the degree of arousal of the organism. These findings led to the

general supposition that under- or over-aroused individuals perform poorly, whereas optimal performance occurs in a moderately aroused state (Hebb, 1955). The U-shaped conceptualization of arousal has maintained a place in mainstream psychology and has been adopted by a number of applied researchers to explain performance in human factors and sport settings (e.g. Easterbrook, 1959; Oxendine, 1984; Raglin and Hanin, 2000). In this perspective, physical exercise has been considered an arousing stimulation of the organism (Cooper, 1973; Davey, 1973) and a U-shaped function between exercise and cognitive performance has been expected (Näätänen, 1973). However, empirical data did not support the hypothesis that performance is an inverted-U function of exercise intensity (for a review, see McMorris and Graydon, 2000). The view that acute aerobic exercise can be considered an arousing stressor is central in the present chapter.

Arousal and activation, terms often used interchangeably, were initially conceived by researchers as unidimensional constructs that ranged on a continuum from sleep to wakefulness (Duffy,1957, 1962; Malmo, 1959). Changes in arousal levels were often linked to the activity of the ascending reticular formation (e.g. Lindsley, Bowden and Magoun, 1949; Moruzzi and Magoun, 1949). According to the unidimensional perspective, there exists a general nonspecific pool of energetic resources that supports all cognitive functions and the amount of available resources allocated to a task depends, among other variables, on an individual's arousal level (e.g. Kahneman, 1973). The unitary perspective has been criticised, however. The low correlations among different measures of arousal obtained by researchers are inconsistent with a unidimensional view of arousal (Lacey, 1967; Eysenck, 1982; Thayer, 1989). The undifferentiated resource view is not compatible with perfect time-sharing of two resource-demanding tasks (Wickens, 1984). Further, neurophysiological evidence reveals that the reticular formation is not a homogenous system but, rather, one that is highly differentiated (Robbins and Everitt, 1995).

In response to these shortcomings, several researchers have proposed that arousal is a multidimensional construct. For instance, on the basis of many animal and human neuropsychological and psychophysiological data, (Pribram and McGuinness,1975; McGuinness and Pribram, 1980) suggested that there is an involuntary and a voluntary mode of attentional control. The involuntary mode involves two basal mechanisms: arousal, a phasic short-lived and reflex response to input; and activation, a tonic long-lasting and involuntary readiness to respond. A third mechanism, effort, coordinates arousal and activation, and allows a voluntary control of attention. Pribram and McGuinness restricted the use of the concept of arousal to be synonymous with the orienting reaction discovered by Sharpless and Jasper (1956), and Sokolov (1960). A response of the arousal mechanism occurs when an input change produces a measurable phasic change in a physiological or behavioural variable over a baseline. In accordance with studies by Berlyne (1960), arousal results when, in the history of the organism's experience, an input is surprising, complex or novel. Such a reaction involves the assumption that the input is matched against some residual of past experience in the organism, that is a residual neuronal model of events. Activation differs from arousal, therefore, in

maintaining a tonic readiness to respond, reflected in an increase in cortical negativity (contingent negative variation – CNV) and tonic heart rate deceleration. Under many circumstances, arousal and activation appear to be forcibly linked. In stressful situations they share the function of reflex coupling input to output (e.g. startle reflex). In the absence of controlled arousal and activation, behaving organisms would be constantly aroused by their movements and moved by arousing inputs. One function of the effort mechanism is to uncouple arousal and activation in order to avoid undesirable reactions.

Recent advances in methods of assessing the structure and function of the brain have provided researchers the means to identify more precisely the neurophysiological components of arousal and activation. The reticular activating system has, for example, been shown to consist of several inter-related arousal systems that are differentiated by specific neurotransmitters (Robbins and Everitt, 1995). Three main systems of neuromodulators have been distinguished: the noradrenergic, the dopaminergic and the serotoninergic systems. Several studies conducted on animals and humans showed that acute physical exercise results in a releasing of brain catecholamines (noradrenaline and dopamine) and indolamines (serotonin or 5-hydroxytryptamine) (see Meeusen and De Meirleir, 1995, for a review). Therefore, a large part of acute and chronic effects of exercise on cognitive processes may be closely related to the catecholaminergic and indolaminergic neuromodulations of neural networks involved in information processing. The noradrenergic system originates from the locus coeruleus in the pons. Neural cell bodies send projections throughout a large part of the neocortex and the hippocampus. Fluctuations in locus coeruleus activity can be observed in cortical electroencephalograms (EEG) and in P300 event-related potentials. Tone, lights or tactile stimuli, as well as noxious or stressful events, result in an increase of the activity of the locus coeruleus, which has been linked to preservation of alertness that aids in detecting sensory signals under high levels of arousal (see Foote, Bloom and Aston-Jones, 1983; Berridge and Waterhouse, 2003; Posner, 1995; Pribram and McGuinness, 1975; Ramos and Arnsten, 2007; Robbins and Everitt, 1995; for reviews). The coeruleo-cortical noradrenergic system appears to have a protective function of maintaining an individual's capacity to maintain discrimination processes under stressful or arousing circumstances. An increase in brain noradrenergic transmission improves the signal-to-noise ratio of evoked responses to environmental stimuli, either by enhancing evoked responses, by suppressing 'background activity' or by a combination of these two effects in several cortical terminal regions, whatever the sensory modality (e.g. Kasamatsu and Heggelund, 1982; Foote, Freedman and Oliver, 1975; Hurley, Devilbiss and Waterhouse, 2004; Moxon *et al.*, 2007; Waterhouse and Woodward, 1980).

The dopaminergic system originates from cell bodies located in the substantia nigra pars compacta and from the ventral tegmentum. Projections from these areas modulate neural activity in (a) the dorsal and ventral striatum, which, in turn, affect the supplementary motor area, premotor area and primary motor cortex and (b) the frontal lobe, and more particularly the medial prefrontal cortex, that underlies

Table 1.4 Two energetical mechanisms activated by an acute bout of steady-state aerobic exercise.

Energetical mechanism	Neurotransmitter system	Brain localization	Main function	ERP index
Arousal	Noradrenaline	Locus coeruleus	Filtering inputs	P300
Activation	Dopamine	Substantia nigra pars compacta	Energizing outputs	CNV

Note: ERP: Event-related potential; P300: Positive cortical wave observed 300 milliseconds after the occurrence of response signal in a reaction time task; CNV: contingent negative variation.

executive functions. These pathways affect the activation or energization of behaviour and account for the vigour and frequency of behavioural outputs (Robbins and Everitt, 2007). Characteristics of noradrenergic and dopaminergic neuromodulator mechanisms are summarized in Table 1.4. The serotoninergic system originates from cell bodies located in the raphe nucleus. Neurons from this system dampen the actions of each of the two preceding systems and promote behavioural inhibition and cortical deactivation (see also Chapter 2).

We saw that exercise has been considered an arousing stressor (e.g. Davey, 1973; Näätänen, 1973; Thayer, 1987), but few investigators have provided a theoretical rationale for a causal link between exercise, arousal, brain catecholamines and improvement in cognitive performance. As stated by McMorris and Graydon (2000), Cooper (1973) was the first author to propose a set of clear arguments based on different studies conducted with animals and humans: (1) synthesis of noradrenaline increases in the brain of the rat during severe and prolonged forced exercise; (2) concentration of plasma catecholamines increases during exercise; (3) brain noradrenergic activity increases during cortical activation; (4) the level of cortical arousal is related to the level of activity of the reticular formation; and (5) exercise can increase the activation of the reticular formation via somatosensory feedback due to the movement of the limbs. Considerable research has provided support for these arguments and today, the peripheral and central arousing effects of exercise are well documented. Acute exercise is widely known to activate both the sympathetic nervous system and the hypothalamo-pituitary-adrenal system, resulting in a release of catecholamines and indolamines, both centrally and peripherally (e.g. Wittert, 2000; Meeusen and De Meirleir, 1995, for reviews). Models and methods presented in the two following sections are compatible with this hypothetical explanation of acute effects of aerobic exercise on cognition.

1.4 Exercise effects and cognitive-energetic models

During the second half of the twentieth century, several cognitive-energetic models synthesising the two main approaches were proposed (see Figure 1.2). In the present section, four of these models will be presented. They provide a heuristic framework for the study of the acute effects of exercise on cognition.

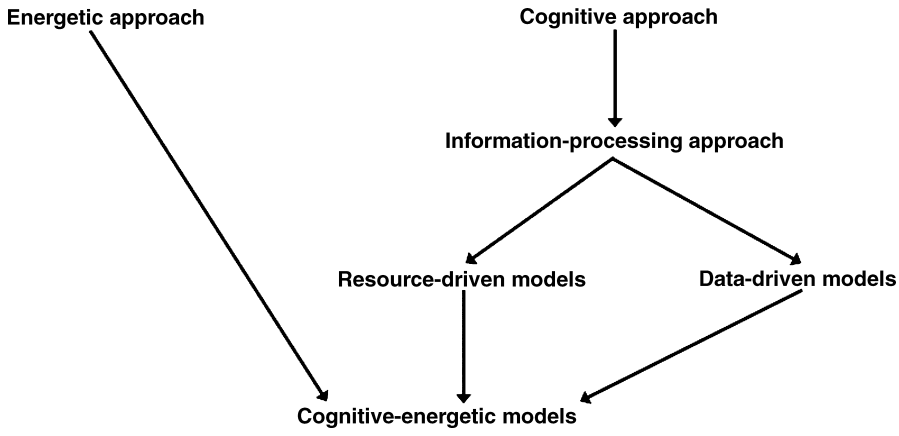

Figure 1.2 A schematic representation of the theoretical roots of cognitive-energetic models.

Kahneman's model (1974)

The first cognitive-energetic model can be found in Kahneman's book '*Attention and Effort*' (1973). Kahneman viewed the amount of resources available at any time as limited. The amount of available resources depends on the level of arousal, which is determined by two sets of factors: (1) the demands imposed by the activities in which the organism engages, or prepares to engage in; and (2) miscellaneous sources of arousal such as intensity of stimulations, psychostimulant effect of drugs, anxiety or acute effect of aerobic exercise. Resources are accumulated in a single undifferentiated pool of resources (see Figure 1.3). The amount of available resources and the effort invested performing a task can be measured through several measures of arousal (e.g. pupil dilatation, heart-rate variability). An allocation policy mechanism directs and supervises the allocation of resources. The strategy of allocation is influenced by enduring dispositions (e.g. pre-wired and automatic behaviours such as the automatic and involuntary orientation towards a novel stimulus), momentary intentions (e.g. reaching a task-related goal) and feedback from ongoing activities (e.g. feedback of success).

According to Kahneman, the level of arousal corresponds to the amount of available attentional resources, while effort is understood to be the voluntary attention allocated to a task. In this perspective, decrements in performance are due to demands of concurrent activities or processes which exceed the amount of available resources. The notions of 'processing limitations' and 'effort invested to perform a task' led Norman and Bobrow (1975) to introduce the very interesting concepts of data-limited and resource-limited processes. Whenever an increase in the amount of processing resources can result in improved performance, the performance on that task is said to be resource-limited; and whenever performance is independent of processing resources, the performance is said to be data-limited (see Figure 1.4). In the resource-limited region of the performance-resource function,

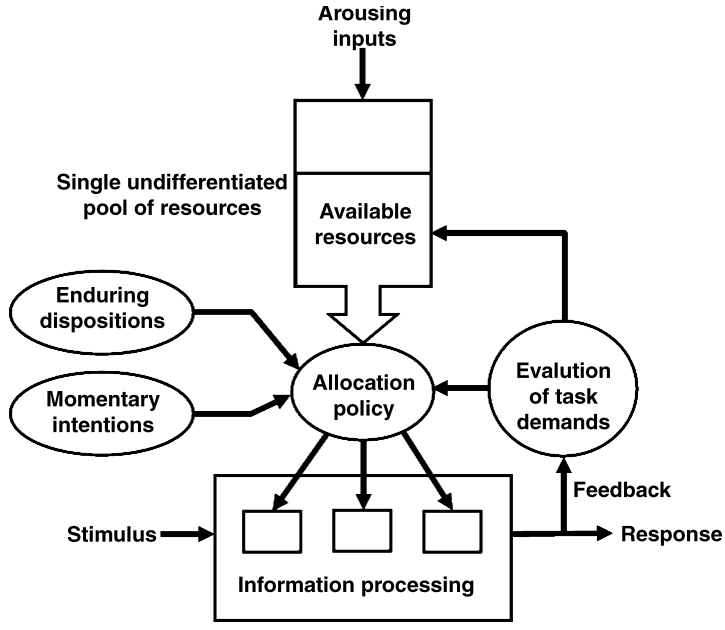

Figure 1.3 Kahneman's cognitive-energetic model. (Modified from Kahneman, 1973.)

performance is assumed to be a monotonically increasing function of the amount of allocated resources to perform the task. Norman and Bobrow distinguished two forms of data limitations: (1) signal data limitations, when the limit to performance depends primarily upon the signal-to-noise ratio and the quality of the input data

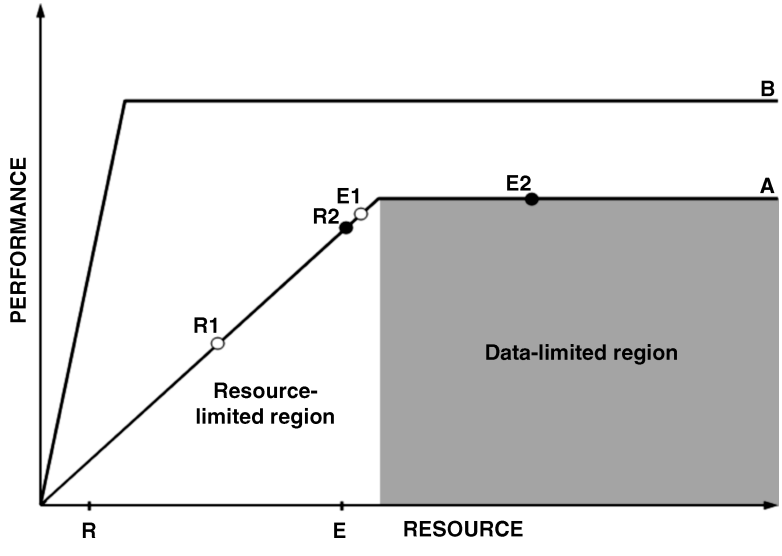

Figure 1.4 The Norman and Bobrow performance-resource function (see text for more explanation).

signal (e.g. detection of a very weak signal in a noisy environment); and (2) memory data limitation, when the limit to performance depends mainly upon the quality of the representation stored in memory (e.g. identifying which of two almost identically oriented presented lines has just been seen). Most tasks involve processes characterized by data-limited and resource-limited regions.

In Figure 1.4, curves A and B represent performance-resource functions for two tasks, respectively task A and task B. Task A requires more resources to be performed than task B. The higher demands of task A can be caused either by a higher complexity, or by a lower familiarity of those performing this task. The resource-limited and data-limited regions are represented only for curve A. The asymptotic level in performance is different for curves A and B suggesting a better performance for task B. Points R and E represent the presumed level of arousal of participants, who were at rest (R) or who exercised (E), during an experiment on the facilitating effect of aerobic exercise on cognitive tasks. In the theoretical framework of Kahneman's model, it is assumed that exercise induces an increase in physiological arousal and then an increase in available resources. If participants perform tasks A and B at rest (R on Figure 1.4) and during exercise (E on Figure 1.4), we will observe a significant improvement in task A, but not in task B. We can conclude from this graph that tasks which require large amounts of resources (task A) are more sensitive to a facilitating effect of aerobic exercise than tasks which require fewer resources (task B). In addition, Humphreys and Revelle (1984) pointed out that stimulant drugs and other arousers (e.g. acute aerobic exercise) are most likely to improve performance of sustained information transfer tasks (e.g. choice reaction time task) when the participants are at a low level of arousal in the placebo or control condition. Imagine participants who perform task A at rest (R1 on Figure 1.4) and during a steady-state aerobic exercise (E1 on Figure 1.4). In this case, we will observe a significant improvement of performance. If, the same participants perform task A with a higher level of arousal at rest (R2 on Figure 1.4) and during exercise (E2 on Figure 1.4), the likelihood to observe a significant improvement is weaker. For that reason, participants involved in an experiment assessing the facilitating effect of aerobic exercise on cognition must be instructed to refrain from drinking stimulant beverages (e.g. coffee, tea, alcohol) just before the experiment. In the same way, it is important to lower the initial arousal level of participants, for example by conducting the experiment early in the morning or increasing time on task.

According to the Kahneman's model, interference between tasks is an increasing function of workload. Workload can be defined as the amount of resources necessary to perform a specific task for a specific participant. At low values of workload, there may be little or no interference between tasks, whereas at high values of workload, the interference may be severe. This interference phenomenon can explain why performance of cognitive tasks can be impaired during exercise. If the walking, running or cycling exercise competes with the cognitive task for resources, we will observe such interference. Knowles (1963) and Rolfe (1973) proposed a workload assessment technique named the 'dual-task' or 'secondary-task' technique, based on the measurement of interferences between two tasks (see Abernethy, 1988, for a review).

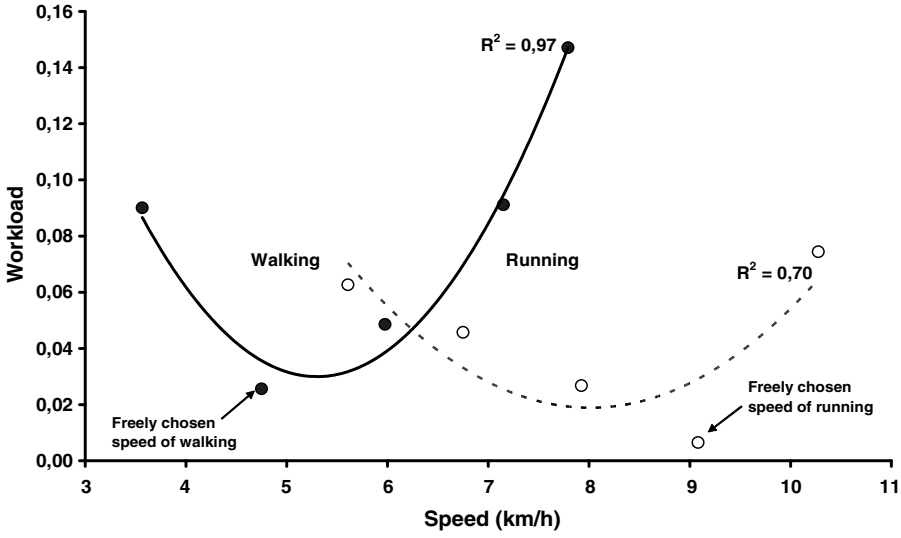

Figure 1.5 Workload of walking and running on a treadmill as a function of speed (Black circles: walking; White circles: running).

In this measurement paradigm, the workload associated with a given task, named the 'primary' task, is measured by assigning the human operator another task, named the 'secondary' task, to perform concurrently with the primary task. Impairment of the secondary task is assumed to be a linear function of workload. By using this dual-task method, it is possible to measure the workload of exercising. A study conducted by Dorgans and Audiffren (2003) showed that the workload of walking and running is the lowest for the freely chosen speed (see Figure 1.5). The primary task consisted of walking or running at specific speeds and the secondary task was a simple reaction time task. Similar results were obtained by Kurosawa (1994) and Brisswalter *et al.* (1995). These results show that it is important to instruct participants to walk, run or cycle at a freely chosen speed to lower the workload of exercise to a minimal value if researchers want to avoid risks of interferences between the cognitive task and physical exercise. Freely preferred locomotor speed can be defined as the speed to which humans adopt the most natural possible gait (Holt, Hamill and Andres, 1991). The speed adopted naturally by participants is related to the resonance frequency in which a human moves in order to optimize his/her efficiency while maintaining a weak energy demand. This speed is automatically adopted by quadrupeds when they change locomotor gait in order to minimize their energy expenditure (Hoyt and Taylor, 1981).

To summarize, Kahneman's model supports four important ideas concerning the effects of exercise on cognition: (1) if exercise increases the arousal level, it increases at the same time the amount of resources available to perform a concomitant cognitive task; (2) resource-limited processes are most likely to be improved by an arousing stressor such as an acute bout of exercise; (3) participants underaroused in

the rest or control condition are most likely to show an improvement in performance in the arousing exercise condition; and (4) impairment of performance in cognitive tasks observed in some experiments assessing the effects of exercise on cognition can be explained by the too high mental workload required by physical exercise (e.g. monitoring the speed of cycling). The second summarized idea is not compatible with some results showing that effortful executive processes are impaired by acute aerobic exercise (Dietrich and Sparling, 2004; Pontifex and Hillman, 2007). This problem comes from the unidimensional modelling of resources reservoir used in the Kahneman's model, in which arousal and on-task effort are confounded. The two following models, which take place in a multidimensional approach of cognitive and energetic interactions, can explain the observation that some cognitive processes are improved by acute aerobic exercise, whereas other are impaired.

Sanders' model (1983)

In the beginning of the eighties, Sanders proposed a heuristic cognitive-energetic model of information processing (Sanders, 1981, 1983, 1998), in which arousal, activation and effort influence specific stages of information processing. Sanders proposed a synthesis of the two major approaches in mental chronometry described earlier: (1) a computational data-driven approach, which emphasizes the structural aspects of the reaction process (e.g. Donders, 1969; Sternberg, 1969b); and (2) an energetic resource-driven approach concerned with capacity limitations, resource allocation and strategic control (e.g. Kahneman, 1973). The Sanders' model includes three aspects of information processing: (1) a cognitive level composed of four processing stages; (2) an energetic level composed of three energetic mechanisms, which allocate processing resources; and (3) an evaluation level that corresponds to an executive process, which manages processing resources (see Figure 1.6). From a large number of reaction time experiments using the additive factors method of Sternberg (1969a, 1998), Sanders argued that arousal is linked to the feature

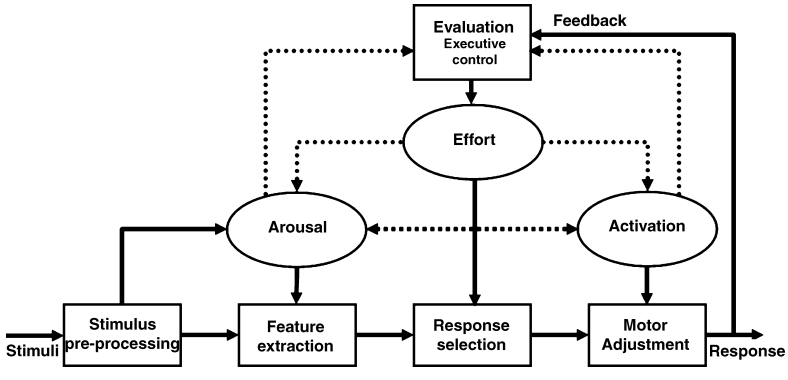

Figure 1.6 Sanders' cognitive-energetic model. (Modified from Sanders, 1983.)

extraction stage; activation influences the motor adjustment stage; and effort is involved in response selection (see Figure 1.6). Stimuli encoded by sensory organs have two dimensions, an energetical dimension, which arouses the organism, and an informational dimension processed by the different stages of information processing. The effort mechanism also serves the function of keeping the basal resources at an optimal level in order to satisfy the demands of the task. The main difference between Kahneman's and Sander's cognitive-energetic models is a shift from a unidimensional conception of resources (one unique reservoir of arousal) to a multidimensional perspective (three supply systems). The three energetic mechanisms bear a close resemblance to those described by Pribram and McGuinness (1975). The Sanders' model is particularly helpful to interpret facilitating or slowing effects of exercise on reaction processes.

In Sander's model, an acute bout of aerobic exercise may increase both arousal and activation mechanisms and then modulate input and output processes. Exercise may also influence decisional processes via the effort mechanism if both the cognitive task and the motor task (e.g. cycling at an imposed speed) consume mental effort. In this case, the amount of effort necessary to perform the cognitive task can be slightly insufficient and lead to a slowing of decisional processes. In the next section, we will see two methods allowing localizing of the acute effects of aerobic exercise in the architecture of the Sanders' cognitive-energetic model.

Humphreys and Revelle's model (1984)

Another cognitive-energetic model using a multidimensional approach of mental energy was developed during the 1980s: the personality, motivation and performance structural model of Humphreys and Revelle (1984). This model integrates two major approaches to the study of human mental performance: the cognitive approach and the differential approach. According to the metaphor of the digital computer used by cognitive psychologists, the human information processing system operates exactly in the same way for everyone. From this perspective, it is coherent and pertinent to study the average of the performances of dozens of subjects to infer general principles of functioning of the information processing system. In contrast, differential psychologists are interested in the variability due to the psychological differences among individuals. Based on the answers of hundreds of participants to questionnaires, they define different personality traits (e.g. high achievers versus low achievers, extroverts versus introverts, individuals who are high or low in trait anxiety). According to some authors using this approach (e.g. Eysenck,1967, 1992; Humphreys and Revelle, 1984), these stable characteristics of personality interact with situational factors (e.g. time of day, time on task, task difficulty) and modulate the information processing. For instance, personality traits can influence baseline arousal level (see Matthews, 1992 for a review) and selective attention (e.g. MacLeod and Matthews, 1988).

In their model, Humphreys and Revelle (1984) showed the effect of three relatively independent personality constructs (impulsivity, achievement motive and trait

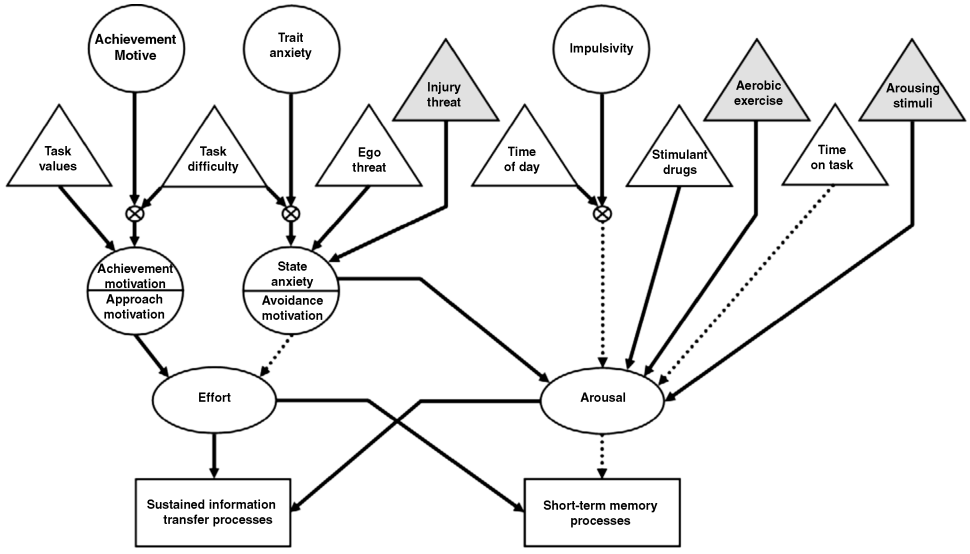

Figure 1.7 Cognitive-energetic model of Humphreys and Revelle (modified from Humphreys and Revelle, 1984). Solid lines represent positive influences and dashed lines represent negative influences. Circles represent latent variables, triangles represent situational variables, ellipses represent energetic mechanisms, and rectangles represent information-processing processes. Achievement motive, trait anxiety and impulsivity are dispositional variables. Circled Xs represent interactive effects. Interaction between dispositional variables and situational variables results in state variables, for instance, achievement motivation and state anxiety. Approach and avoidance motivations are motivational states related respectively to achievement motivation and state anxiety. Shaded triangles have been added to the original model.

anxiety) in combination with six situational moderators (incentives, feedback of success and failure, psychostimulant drugs, ego threat, time of day and time on task) on the two motivational constructs of arousal and on task effort. Figure 1.7 shows a slightly modified version of this model. Three situational moderators have been added: injury threat, aerobic exercise and arousing stimuli. These variables may influence inner states in sport situations. For instance, a young boxer may be simultaneously aroused by growing anxiety due to the threat of an injury caused by the punches of his brutal opponent, by his own movements in the ring and by the applause and cheers of the crowd. The name of several situational variables has been changed to carry meaning related to more recent motivation theories. The variable 'incentives' has been replaced with 'task values' in reference to the *expectancy-value* model (e.g. Wigfield, 1994; Wigfield and Eccles, 1992). In the same way, the variable 'feedback of success/feedback of failure' has been replaced with 'task difficulty' in reference to the theory of *motivational intensity* (e.g. Brehm and Self, 1989). Finally, the short-term memory processes described by Humphreys and Revelle are very similar to the working memory function of the central executive (e.g. Baddeley and Della Sala, 1996; Baddeley and Hitch, 1974). Humphreys and Revelle did not contest

that there are different arousal systems or physiological ways of becoming aroused but, in contrast to Pribram and McGuinness (1979), they considered general arousal a higher-order construct common to various indicants of alertness.

Humphreys and Revelle (1984) distinguished between arousal at the micro and at the macro levels. At the micro level, arousal is very transitory, indexed in milliseconds, may be measured by pupil dilatation, changes in heart rate, changes in the EEG (Kahneman, 1973) and could be assimilated to Pribram and McGuinness (1979) arousal. At the macro level, arousal is of much longer duration, indexed in minutes or in hours, relates to the general feelings of alertness or activation (Thayer, 1989), body temperature (Blake, 1967), hormonal excretions (Frankenhaeuser, 1975), and could be assimilated to stress (Selye, 1976). The arousal mechanism shown in Figure 1.7 corresponds to the macro level arousal described by Humphreys and Revelle.

The theoretical framework developed in the cognitive-energetic model of Humphreys and Revelle (1984) makes two main contributions to the assessment of exercise effects on cognition. First, personality traits interact with situational moderators resulting in a change in arousal level. Two independent personality traits have been related to arousal: anxiety and impulsivity. On the one hand, people who are generally highly anxious have, on average, a higher level of arousal than people with low anxiety levels. On the other hand, low impulsives are more aroused in the morning than high impulsives. These two interactions suggest that people who are highly anxious and low on impulsivity should be less sensitive to the arousing effect of exercise in the morning. In other words, individual differences in personality traits related to arousal increase the inter-individual variability of the effect size of exercise. Researchers interested in the effects of exercise on cognition must be aware of this potential problem and take account of individual differences in their research protocols. Second, arousal seems to have opposite effects on tasks involving sustained information transfer processes (e.g. choice reaction time task) and tasks tapping short-term memory processes (e.g. letter memory task). The model predicts that an acute bout of aerobic exercise improves choice reaction time but impairs the number of recalled items in a working-memory task. This prediction is particularly important and may explain some controversial results in the literature. This prediction is also compatible with the hypofrontality theory developed by Dietrich (2003, 2006; Chapter 3 of this book) and merits more experimental testing.

Hockey's model (1997)

In the tradition of cognitive energetic models, Hockey (1993, 1997) proposed a compensatory control model, which accounts for the different patterns of effects on performance observed under stress and high workload (see Figure 1.8). The main contribution of Hockey's model is to distinguish two performance regulation loops: (1) an effort-based compensatory control mechanism, which maintains task performance under disturbance from stressors (e.g. noise, sleep deprivation) and prevents

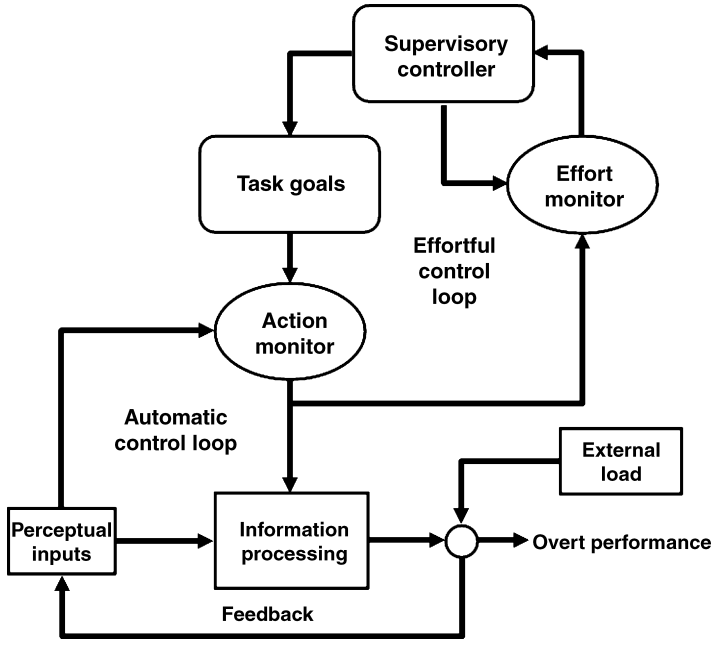

Figure 1.8 Hockey's compensatory control model of performance regulation. (Modified from Hockey 1993, 1997.)

the loss of task goals, particularly under high processing demands (e.g. a very difficult task) or competition for resources from other tasks (e.g. dual-task situation) (effortful control loop in Figure 1.8); and (2) an automatic control mechanism, which functions without effort and concerns the regulation of well-learned skills under the guidance of well-established goals (e.g. expert basketball player running while dribbling ball) (automatic control loop in Figure 1.8).

Hockey (1997) gave a central role to the compensatory effort as a main explanatory mechanism of performance under stress, which occurs when there is a mismatch between required and available resources. Hockey argued that the maintenance of performance stability under demanding conditions is an active process under the control of the individual (supervisory controller in Figure 1.8), requiring the management of cognitive resources through the mobilization of effort. The *action monitor* (see Figure 1.8) compares target outcomes with current outcomes. If a discrepancy is detected, adjustment in resource allocation, speed, timing and/or memory-use is carried out automatically until the discrepancy is reduced to keep it within acceptable limits. For instance, during incremental exercise, the action monitor adjusts the motor command to cope with the increase in workload. A disruption of equilibrium may be brought about either by unexpected surges in external load (e.g. a boar crossing the road just in front of a car while the driver speaks with his/her passenger) or a fall in internal resources (e.g. fatigue). It is assumed that the usual and frequent discrepancies within the normal range are managed through

the use of an automatic routine correction mechanism (automatic control loop in Figure 1.8).

The *effort monitor* mechanism (see Figure 1.8) is assumed to be sensitive to increasing control demands in the lower loop ensured by the automatic control mechanism. An increase of control demands may happen when there is a failure to resolve the discrepancy between target and current outcomes, too slow a rate to solve the discrepancy or too high a variability of outcomes. The *supervisory controller* (see Figure 1.8) detects any failure to solve the discrepancy and selects a mode of regulation among several available strategies. Another important contribution of Hockey (1997) is to distinguish two control options for resolving the discrepancy between increasing demands and availability of effort: (1) in the first option, the allocation of effort is increased to cope with the new level of demand and the target outcome can be maintained; and (2) in the second option, task goal and target outcome are adjusted downward and the allocation of effort is maintained at its initial level.

According to Hockey (1997), it is very important to take into account the compensatory trade-off between cognitive goals and effort in order to understand the performance changes observed under stress and high workload. Hockey identified four latent breakdowns in performance, evidence of the manifestation of the same regulatory mechanism: (1) selective impairment of low-priority task components (e.g. narrowing of attention); (2) within-task shift to less effortful strategy (e.g. less use of working memory, shift in the speed–accuracy trade-off); (3) increase in activation of physiological systems and in affective response involved in emergency reactions (e.g. sympathetic and neuroendocrine stress reactions); and (4) post-task preference for low-effort strategies due to fatigue after-effects. The Hockey model is very interesting for studying the effects of exercise on cognition, because it allows for interpreting shifts in strategy that have been observed in several experiments (e.g. Audiffren, Tomporowski and Zagrodnik (2007b)).

Table 1.5 summarizes the contributions of the four cognitive-energetic models to the understanding of the different possible concomitants or after-effects of steady-state exercise on cognitive task performance.

1.5 Sensorimotor and cognitive functions affected by exercise

Localizing the effects of stressors, such as physical exercise, in the architecture of the information-processing system can be only addressed if researchers are able to divide the complex system into functionally distinct stages, processes and functions. In this section, five methods that allow us to identify the locus of influence of the effects of acute bouts of aerobic exercise are presented along with some examples. For a very interesting critical overview of several methods separating cognitive processes, readers are referred to Sternberg (2001). The five presented methods can be used either separately or simultaneously in the same experiment, and, in some cases, even in the same task.

Table 1.5 Contributions of cognitive energetic models to the understanding of effects of steady-state aerobic exercise on information processing.

Cognitive energetic model	Direction of the effect	Explanation of the effect	Time of the effect
Kahneman's model	Improvement of performance	Aerobic exercise increases the amount of available resources	During and after
Kahneman's model	Impairment of performance	Exercise and cognitive task compete for resources	During
Kahneman's model	Impairment of performance	Exhaustion of resources in the case of very long exercise	During and after
Sanders' model	Improvement of sensory and motor processes	Aerobic exercises increases the level of arousal and activation	During and after
Sanders' model	Impairment of decisional processes	Exercise and cognitive task compete for effort	During
Humphrey and Revelle's model	Improvement of reaction processes	Aerobic exercise increases arousal	During and after
Humphrey and Revelle's model	Impairment of short-term memory processes	Aerobic exercise increases arousal	During and after
Hockey's model	Shift to an easier strategy	Exercise and cognitive task compete for effort	During and after

Note: The direction of the effect (column 2) concerns the performance of the cognitive task. The time of effect (column 4) indicates if the effect may be observed during, just after, or both during and just after exercise.

Task-comparison method

This method is the oldest method used by psychologists to measure the speed of mental processes. It is also used by neuropsychologists to determine which cognitive functions are deteriorated by brain lesions. The logic of this method is simple: if two tasks, A and B, involve different cognitive processes and a given factor X influences the performance of only one of them, for instance task A, then one can conclude that factor X selectively influences processes involved in task A and not those involved in task B. For example, Donders (1969) assumed that simple reaction time tasks (SRT) do not require stimulus discrimination or response selection, whereas choice reaction tasks (CRT) do. In the same way, Boutcher (2000) gave examples of cognitive tests used to study fitness effects on cognitive performance in ageing; he assumed that the Stroop colour test taps attentional processes, whereas the Sternberg number task involves memory processes.

The Donders (1969) subtraction method is certainly the most venerable task-comparison method. In the example above, by subtracting SRT from CRT we obtain the duration of all processes included in CRT but not in the SRT task. The subtraction method has been criticized by many authors (e.g. Pachella, 1974), but is still used in brain imagery and cognitive psychology. One limit of this method is the a priori assumption that a particular task taps a specific cognitive process.

It is important to distinguish the task-comparison method from the four other methods presented in the five following sub-sections. The goal of the task-comparison method is to show that a factor (e.g. aerobic exercise) has a selective influence on different tasks, each involving a different complex process. In contrast, the goal of the five other methods is to decompose or partition a complex process involved in a task into separate sub-processes (Sternberg, 2001). For that reason, task comparison can be considered as a less precise and rougher method of localizing the effect of exercise in the cognitive architecture. In addition, the task-comparison method requires a theory which can justify how the different tasks used in the experiment involve distinct complex processes.

Several studies have used the task comparison method to examine the effects of acute aerobic exercise on cognitive processes (e.g. Adam *et al.*, 1997; Audiffren, Tomporowski and Zagrodnik, 2008; Dietrich and Sparling, 2004; Paas and Adam, 1991). In these four studies, the authors predicted different patterns of results for the two tasks they selected. Results are summarized in Table 1.6. This set of experimental data suggests that tasks requiring sustained information transfer (Humphreys and Revelle, 1984), such as choice reaction time tasks, are improved by concomitant acute aerobic exercise, whereas tasks involving working memory processes, such as the Paced Auditory Serial Addition task, are impaired or require a shift toward a less effortful strategy. These results can be interpreted in the theoretical framework of cognitive energetic models and Dietrich's hypofrontality model.

Within-task subtraction method

The subtraction method was also used to compare two or more different conditions within the same task. In this case, the task involves a mixture of different kinds of trials. For instance, in an attempt to distinguish automatic and conscious orienting of attention, Posner and Snyder (1975) used a subtraction method to calculate the cost and benefit of attentional orienting. For this purpose, they developed a reaction time procedure in which the imperative response stimulus is preceded by a priming stimulus. This procedure was later used to study the covert orienting of visual attention. Covert attention corresponds to attending the location of a stimulus according to preliminary information (e.g. priming stimulus) without any change in eye or head position. When the priming stimulus occurs in a specific location, it leads to an automatic orienting of attention, which improves information processing and decreases reaction time if the response stimulus occurs within 50–150 ms after the occurrence of the priming stimulus. This covert and automatic shift of attention is

Table 1.6 Synthesis of studies using the task-comparison method to assess the effects of acute aerobic exercise on cognitive processes.

Tasks	Direction of effect	Time of measurement	Characteristics of exercise	Reference
Choice reaction time	Improvement			
Short-term memory	Impairment	During	20 min cycling at 75% MAP	Paas and Adam, 1991
Choice reaction time	Improvement	During	20 min cycling at 75% MAP	Adam *et al.*, 1997
Short-term memory	Speed-accuracy tradeoff			
Wisconsin card sorting	Impairment	During	45 min cycling or running at 70–80% HRmax	Dietrich and Sparling, 1994, exp. 1
Brief Kaufman intelligence	No effect			
Paced auditory serial addition	Impairment	During	65 min running at 70–80% HRmax	Dietrich and Sparling, 1994, exp. 2
Peabody picture vocabulary	No effect			
Choice reaction time	Improvement	During	35 min cycling at 90% VT	Audiffren *et al.*, 2008
Random number generation	Shift toward a less effortful strategy			

Note: MAP: Maximum aerobic power; HRmax: Maximum heart rate; VT: ventilatory threshold.

interpreted as a way of guiding the eyes to appropriate areas of the visual field (Posner, 1995).

The manipulation of the stimulus onset asynchrony (SOA) between the priming stimulus and the response stimulus allows one to study the efficiency of automatic orienting of attention. Conscious attention responds to the probabilities of different events, speeding up reactions when an expected event occurs. In the priming procedure, conscious attention can be manipulated by varying the probability of validity of preliminary information given by the priming stimulus. If the information given by the priming stimulus is valid, the imperative response stimulus occurs in the location indicated by the priming stimulus and reaction time is quicker. Inversely, if the information given by the priming stimulus is invalid, the response stimulus occurs in an unexpected location and the reaction is slowed. When there is a high probability that prime location matches response signal location (e.g. $p = 0.80$), two situations may happen: (1) if prime location really matches response signal, both automatic and conscious attention facilitates performance; and (2) if prime location

does not match response signal location, only conscious attention is responsible for reorienting of attention and slowed performance. According to Posner and Snyder, facilitation of performance can be due either to conscious or to automatic orienting of attention, whereas impairment of performance is due only to conscious attention. By subtracting reaction time observed in the valid or neutral prime condition from the reaction time observed in the invalid prime, we obtain an index of the attention reorienting cost.

The priming procedure was used by Pesce and her co-workers to study the arousing effect of aerobic exercise on conscious and automatic orienting of attention (Pesce *et al.*, 2003). Probability of prime validity (0.80 or 0.20) and SOA (150 or 500 ms) were manipulated. Participants had to perform the reaction time task while cycling (50–60 rev.min^{-1}) at 60% heart rate reserve. Pesce and collaborators found interesting results in their first experiment. They observed a third-order interaction between prime-response signal matching, SOA and exercise level (at rest or while exercising). The interaction was mainly due to the fact that the mismatching condition led to slower reaction times at rest than during exercise only with longer SOA. This result strongly suggests that the arousing effect of aerobic exercise improves conscious reorienting of attention.

Posner's priming procedure used a subtraction method to isolate the conscious reorienting of attention process. In the same way, the subtraction method was used in the Stroop task and the Flanker task to isolate conflict or inhibiting processes (see Eriksen, 1995; MacLeod, 1991, for reviews), and in the switching task to isolate shifting processes (Rogers and Monsell, 1995; Vandierendonck, 2000). These three kinds of tasks were used in protocols assessing the effect of acute aerobic exercise on executive processes (Coles and Tomporowski, 2008; Hillman, Snook and Jerome, 2003; Hogervorst *et al.*, 1996; Sibley, Etnier and Le Masurier, 2006; Pontifex and Hillman, 2007; Tomporowski and Ganio, 2006). Results of these studies are summarized in Table 1.7. No clear tendency emerges from this set of experimental data, but executive functions seem to be improved by acute aerobic exercise.

Additive factors method

This method, conceived by Sternberg (1969a, 1998), is based on the discrete serial information processing model (Sanders, 1990). The additive factors method (AFM) considers reaction time as the sum of the duration of each of the processing stages that take place between the occurrence of the stimulus and the initiation of a response. For each stage, at least one computational factor (e.g. stimulus–response compatibility) exists that directly and selectively affects its duration without modifying processing quality. If assumptions of the AFM are respected, the following logic may be applied: (1) when two factors influence no stage in common, one can expect their effects to be additive; conversely, (2) when two factors influence at least one stage in common, one can expect their effects to interact in an overadditive manner. It is important to note that the logic of the AFM is compatible with other models of information processing such as the cascade model (McClelland, 1979) and other

Table 1.7 Synthesis of studies using the within-task subtraction method to assess the effects of acute aerobic exercise on cognitive processes.

Trials	Cognitive process	Direction of effect	Time of measurement	Characteristics of exercise	Reference
Valid vs invalid prime	Conscious reorienting of attention	Improvement	During	12 min cycling at 60% VO_2max	Pesce *et al.*, 2003
Colour naming vs colour-word interference	Inhibition processes	Improvement	After	60 min cycling at 75% MAP	Hogervorst *et al.*, 1996
Colour naming vs colour-word interference	Inhibition processes	Improvement	After	20 min jogging at 3–6 METs	Sibley *et al.*, 2006
Congruent vs incongruent	Inhibition processes	No effect on RT data	After	30 min running at 83.5% HRmax	Hillman, *et al.*, 2003
Congruent vs incongruent	Inhibition processes	No effect on RT data	During	6.5 min cycling at 60% HRmax	Pontifex and Hillman, 2007
Switch vs non switch	Switching processes	No effect	After	30 min cycling at 60% VO_2max	Coles and Tomporowski, 2008
Switch vs non switch	Switching processes	No effect	After	30 min cycling at 60% VO_2max	Tomporowski and Ganio, 2006

Note: RT: reaction time; VO2max: Maximum oxygen uptake; MAP: Maximum aerobic power; MET: Metabolic equivalent; HRmax: Maximum heart rate.

models with temporally overlapping processes (Miller, van der Ham and Sanders, 1995). On the basis of the literature on the additive stage structure of traditional choice reactions, Sanders (1983) distinguished four well-established stages resulting from the robust pattern of additivity between four computational factors: (1) preprocessing stage, influenced selectively by signal intensity; (2) feature extraction stage, influenced by signal quality; (3) response selection stage, influenced by stimulus–response compatibility; and, finally, (4) motor adjustment stage, influenced by foreperiod duration (see Figure 1.6). Several authors have used the additive factors method to localize the effects of acute bouts of aerobic exercise in the sequence of information processing stages (e.g. Arcelin, Delignières and Brisswalter, 1998; Davranche and Audiffren, 2004; Davranche *et al.*, 2005a) (see Table 1.8, for a synthesis). For instance, in the Arcelin *et al.* study, participants performed a choice reaction time task during a cycling exercise at 60% of maximal aerobic power or at rest. Three computational factors were manipulated in combination with exercise level (at rest versus while exercising): signal quality, stimulus–response compatibility and foreperiod variability. Arcelin and collaborators observed that the facilitating effect of exercise and the effects of the three manipulated computational factors are additive on mean reaction time and first quartile of reaction time distribution. However, they observed a significant interaction between the effect of exercise and foreperiod variability on the third quartile of reaction time distribution. The effect of acute aerobic exercise was larger for varied foreperiod duration than for fixed foreperiod duration. This overadditive interaction suggests that aerobic exercise improves motor preparatory processes. Results obtained with the AFM are summarized in Table 1.8.

Fractionation of reaction time

The locus of the effect of exercise can also be addressed by fractionating the reaction time, with respect to a change in electromyographic (EMG) activity of the response agonist muscle, into two components: the time interval between the onset of the response signal and the onset of EMG activity of the response muscle, termed premotor time (PMT), and the time interval between the onset of EMG activity and the onset of the required motor response, termed motor time (MT) (Botwinick and Thompson, 1966). MT reflects the duration of the electromechanical transduction within muscle fibres, whereas PMT reflects the duration of all earlier stages. The duration of MT is included in the motor adjustment stage described by Sanders (1990). By separating PMT and MT, it is possible to determine whether the facilitating effects of acute bouts of exercise on RT takes place before or after the onset of EMG activity and, therefore, whether it influences early cortical integration processes or late motor processes (Hasbroucq *et al.*, 2002). Three studies used the fractionation method to localize effects of exercise (e.g. Audiffren, Tomporowski and Zagrodnik, 2008; Davranche *et al.*, 2005a, Davranche, Audiffren and Denjean, 2006a). Results of these three studies are summarized in Table 1.8. Two of these studies are presented in Chapter 7.

Table 1.8 Synthesis of studies using a process decomposition method to determine the locus of influence of the facilitating effect of exercise in the information processing flow.

Inference method	Cognitive stage or function	Time of measurement	Characteristics of exercise	Reference
Additive factors method	Sensory processes	During	15 min cycling at 50%MAP	Davranche *et al.*, 2005, 2006
Additive factors method	Motor processes	During	10 min cycling at 60% MAP	Arcelin *et al.*, 1998
			15 min cycling at 50% MAP	Davranche *et al.*, 2005, 2006
RT fractionation	Motor processes	During	35 min cycling at 90% VT	Audiffren *et al.*, 2008
Signal detection theory	Sensory processes	After	30 min running at FCS	Audiffren, *et al.*, 2007
Factor analysis method	Inhibitory processes	During	35 min cycling at 90% VT	Audiffren *et al.*, 2008

Note: Column 1: Method of inference used to localize the effect; Column 2: Information processing stage or cognitive function affected by exercise; third column: time of measurement of the cognitive task; Column 3: Time of measurement of the cognitive task; MAP: Maximum aerobic power; VT: ventilatory threshold; FCS: Freely chosen speed.

Signal detection theory

This theory allows the separation of two hypothetical processes that underlie performance in many tasks: a sensory process and a decision process (Green and Swets, 1966). The measure of the sensory processes (e.g. d-prime or d′) is influenced by sensory factors, such as stimulus properties, but not by decision factors, such as rewards and penalties. Conversely, the measure of decision processes (e.g. bias or β) is influenced by decision factors but not by sensory factors. Signal detection theory (SDT) was initially applied whenever subjects had to detect a specific event within noise or to discriminate between two stimuli. Three tasks are usually used by SDT researchers to calculate SDT indices: yes/no tasks, rating tasks and forced-choice tasks. For instance, in yes/no tasks, a very weak visual signal is presented during 'signal + noise' trials and nothing at all during 'noise' trials. After each trial, the subjects indicate whether a signal was present or not. On 'signal + noise' trials, 'yes' responses are correct and are termed hits. On 'noise' trials, 'yes' responses are incorrect and are termed false alarms. The hit rate and the false-alarm rate fully describe performance in a yes/no task, and more generally in a SDT task. Sensory sensitivity (d′) and response bias (β) are calculated from hit and false-alarm rates (see Stanislaw and Todorov, 1999, for calculation formula).

Audiffren, Abou-Dest and Possamai (2007a) used the SDT to assess the effect of two aerobic exercises, walking and running for 30 minutes at a freely chosen speed on a treadmill, on sensory decision processes. Participants had to decide if they

perceived the flickering of a light at rest, just after the end of exercise, and 30 minutes after the post-exercise test. For retinal reasons, humans do not perceive the flickering of a light above 46–50 Hz; this visual phenomenon is called fusion and is used for many purposes, such as for moving pictures. In half of the trials the light flickered at 50 Hz, and in the other half at 80% threshold of flickering perception. Audiffren and collaborators chose a critical flicker/fusion frequency task because it is well known to be very sensitive to psychotropic drugs (Hindmarch, 1982; Parrott, 1982). In addition, several studies showed that aerobic exercise improves flickering or fusion detection (Davranche and Audiffren, 2004; Davranche and Pichon, 2005) and contrast sensitivity (Woods and Thomson, 1995). In their study, Audiffren, Abou-Dest and Possamai (2007a) showed that sensory sensitivity increased just after the 30 minutes bout of walking or running and returned to baseline 30 minutes after cessation of exercise. These results confirmed that acute aerobic exercise influences early sensory processes; they are summarized in Table 1.8.

Factor analysis method

This method separates a latent variable (e.g. state anxiety) into several components with the help of exploratory or confirmatory factor analyses. For instance, using a confirmatory factor analysis (CFA), Miyake *et al.* (2000) showed that the latent variable 'executive function' can be separated into three sub-components, namely: (1) shifting between tasks or mental sets, (2) updating and monitoring of working memory representations, and (3) inhibition of dominant pre-potent responses. In other respects, Towse and Neil (1998), Towse and McLachlan (1999), Miyake *et al.* (2000) and Friedman and Miyake (2004) performed a principal component analysis (PCA) on a set of randomness indices used in random number generation (RNG) tasks and found that they loaded on three components. Two of these components matched with two of the sub-components extracted by Miyake and his colleagues. The first component had high loadings for the indices that seem to be more sensitive to the degree to which stereotyped sequences are produced (e.g. turning point index, adjacency index, variability of phase lengths) and was interpreted as reflecting the 'inhibition of pre-potent responses' process. The second component had high loadings for the indices that seem to assess the degree to which each number is produced equally frequently (e.g. redundancy index, coupon score, mean repetition gap) and was assimilated to the 'updating of working memory' process.

The use of these two groups of RNG indices that tap selectively different sub-components of the executive function allows localizing more accurately the effect of an arousing stressor on executive processes. This approach was used by Audiffren, Tomporowski and Zagrodnik (2007b) to study the effect of an acute bout of aerobic exercise on RNG indices. In their experiment, participants performed the RNG task at rest and while cycling at 90% of ventilatory threshold. Their study showed two interesting results: (1) aerobic exercise modulated the inhibition function but not the updating function; and (2) participants shifted toward an easier strategy during exercise in order to generate random sequence of numbers. The second result was

larger in the starting period of exercise, suggesting an effortful monitoring of the motor task.

Other ingenious methods developed by cognitive psychologists are available but have not yet been used to localize the effects of acute aerobic exercise in the cognitive architecture, for instance Robert's multiplicative factor method (Roberts, 1987; Sternberg, 2001) and Jacoby's process dissociation procedure (Jacoby, 1991). Results presented in this section suggest that the arousing and facilitating effect of an acute bout of aerobic exercise influences selectively some, but not all, sensorimotor and cognitive processing stages and functions. Table 1.8 summarizes the main results obtained with the four methods. Further experiments must be conducted to delineate precisely which sensorimotor and cognitive functions are improved by acute exercise, which ones are impaired and which ones are not affected.

1.6 Limits of the cognitive-energetic approach and future perspectives

The examination of the effects of exercise on psychological functions is a good example of an interdisciplinary research topic. This kind of research needs the integration of concepts and methodologies that come from many different disciplines, such as cognitive psychology and exercise physiology. We saw in the preceding sections that cognitive psychology alone cannot explain the variability of performance under different environmental stresses (e.g. heat, hypoxia, hyperpressure) or internal states of the organism (e.g. emotion, sedative drugs, fatigue and arousal induced by exercise) (Hockey, Coles and Gaillard, 1986). Other disciplines such as energetic psychology and differential psychology are necessary to study the interaction between physical exercise and psychological functions. In this section, several proposals will be made in order to integrate other disciplines, such as neurosciences and related sub-disciplines such as psychopharmacology, psychobiology and psychophysiology. They should delineate the neurophysiological mechanisms that underlie improvements or impairments of performance and the shift in strategy observed during and following acute bouts of exercise.

Three main levels of integration between cognitive-energetic psychology and neurosciences can be distinguished (Requin, 1986): (1) at the first and lowest level, researchers observe a co-existence or temporal coincidence between one behavioural phenomenon and one physiological or neurophysiological phenomenon; (2) at the second level, researchers predict and test an isomorphic relationship between a structural model of information processing and the anatomo-functional organization of the nervous system; and (3) at the third and highest level, researchers can demonstrate the univocal nature of both cognitive-energetic and neurophysiological models. The work of Chmura, Nazar and Kaciuba-Uscilko (1994) is a good example of the co-existence between behavioural and physiological phenomena related to the effects of exercise on information processing (level 1 of integration). These authors showed a curvilinear relationship between speed of choice reaction time (CRT) and

plasma noradrenaline level: CRT was significantly faster just after the adrenaline threshold than at rest and during exercise at maximal oxygen uptake. However, McMorris and Graydon (2000) stated that changes in plasmatic catecholamines concentration do not mirror changes in brain catecholamines concentration.

To my knowledge, there is no research devoted to the study of acute exercise and cognition that belongs to levels 2 and 3 of interdisciplinary integration of cognitive-energetic psychology and neurosciences. However, in order to illustrate these two levels of integration, I propose an example of possible future research for them. The first example is based on predictions made by the Sanders (1983) cognitive-energetic model and by the Robbins and Everitt (1995) neurophysiological and multidimensional model of arousal. One could test the following cascade of hypotheses in the same experiment: (1) aerobic exercise increases arousal via the locus coeruleus; (2) brain noradrenaline released by the locus coeruleus improves the signal-to-noise ratio in sensory processes; (3) sensory sensitivity in a signal detection task is improved during exercise by comparison to rest; and (4) efficiency of neural networks involved in sensory processes are improved during exercise by comparison to rest.

This experiment could be carried out by measuring simultaneously, while participants exercise or rest, the subjective feeling of arousal, the performance in a sensory detection task, the brain noradrenaline concentration and evoked potentials. One would expect an increase of the following behavioural and neurophysiological indices during exercise by comparison to rest: (1) subjective perception of arousal; (2) sensory sensitivity d′ index, (3) brain noradrenaline concentration; and (4) amplitude of evoked potential. Such results would have strong explanatory implications for cognitive-energetic psychologists and neuroscientists concerning the understanding of the facilitatory effect of exercise on sensory processes. It would be more difficult to reach the third level of integration. This level proposes to manipulate the level of arousal induced by exercise (e.g. three levels of exercise intensity), to measure the signal-to-noise ratio in neural networks involved in the signal detection task and to show a univocal relationship between variations in physiological arousal and variations in signal-to-noise ratio at the neuronal level. This kind of experiment is currently possible in animals but not in humans. Such results would, however, settle much of the debate on the nature of the facilitating effect of exercise on sensory processes. The following sub-sections propose different interdisciplinary approaches which might contribute to the better understanding of neurophysiological mechanisms underpinning the facilitating and debilitating effects of exercise on cognitive processes.

Contributions of psychopharmacology

Psychopharmacology is the study of drug-induced changes in mood, sensation, information processing, cognitive functioning and behaviour. A major goal of psychopharmacology is to explain how psychotropic drugs alter mental states and mental processes by modifying neurophysiological and biochemical mechanisms in

the central nervous system. Psychopharmacology has been extensively used in humans to study the effect of psychoactive drugs on attention, arousal and information processing (e.g. Clark, Geffen and Geffen, 1987; Coull *et al.*, 1995; Halliday *et al.*, 1994; Hou *et al.*, 2005; Mehta and Riedel, 2006; Müller, von Cramon and Pollmann, 1998). Few studies have combined the use of psychoactive drugs and exercise (e.g. Gualtieri *et al.*, 1986; Hogervorst *et al.*, 1999). The main interest of psychoactive drugs is that they can influence a specific neurotransmitter system selectively. For instance, it could be very interesting to use a psychopharmacological agent well known to decrease brain noradrenergic transmission and a placebo at rest and during exercise. If, the arousing effect of aerobic exercise is due to an increase in activity level of this specific neurotransmitter system, the effect size of the facilitating effect of exercise on cognitive processes would decrease, or the effect would disappear, in the drug condition by comparison to the placebo condition. In the same way, it could be interesting to combine the arousing effects of exercise and psychostimulant drugs to examine the pattern of their interaction in the light of the Sternberg's AFM. If an overadditive interaction is observed, one could conclude that both arousing affects have the same locus of influence in the information processing flow, suggesting a common energetic mechanism. In contrast, if an additive pattern is observed, one could conclude that both arousing agents affect different stages of processing and perhaps are underpinned by independent energetic mechanisms.

Table 1.9 provides a list of psychoactive drugs used in human research, which enhance or impair brain noradrenergic and dopaminergic systems.

Contributions of psychobiology

Psychobiologists are interested in measuring biological variables (e.g. the concentration of some molecules synthesized in the brain) in an attempt to relate them quantitatively or qualitatively to psychological or behavioural variables. For instance, if acute effects of aerobic exercise on information processing are due to brain noradrenergic and/or dopaminergic modulation of neural networks involved in sensory, motor and associative cortices, it would be useful to measure the brain noradrenaline (NA) and dopamine (DA) concentrations during or following exercise. Different techniques measuring the concentration of catecholamines directly in the

Table 1.9 Drugs commonly used in human to enhance or impair brain noradrenergic and dopaminergic systems.

Type of psychoactive drug	Brain noradrenergic system	Brain dopaminergic system
Stimulant	Desipramine, Yohimbine, Modafinil	Bromocriptine, Levodopa, Methamphetamine, Methylphenidate, Pergolide
Sedative	Clonidine	Chlorpromazine, Droperidol, Haloperidol, Sulpiride

brain are available in animals, but are too invasive to be used in humans. In man, evaluation of central NA metabolism is based on the measurement of 3-methoxy 4-hydroxyphenylglycol (MHPG) in blood or urine. This molecule is the major metabolite of brain NA. It is able to cross the blood–brain barrier and is excreted in urine. However, urinary MHPG may also be derived from peripheral NA. Several studies have shown that two forms of urinary MHPG can be differentiated: (1) a sulfate form, which can be considered a good index of brain NA; and (2) a β-glucuronide form, which can be considered a more sensitive indicator of peripheral NA metabolism (e.g. Peyrin, 1990; Peyrin and Pequignot, 1983; Peyrin *et al.*, 1985; Yao *et al.*, 1997). However, it is important to note that more recently, Goldstein, Eisenhofer and Kopin (2003) suggested that MHPG sulfate metabolites derive mainly from noradrenaline release in the periphery rather than in the brain.

Two studies have assessed the relationship between exercise, mental performance and MHPG (McMorris *et al.*, 2008a; Peyrin *et al.*, 1987). The study conducted by McMorris and co-workers measured the plasma concentration of MHPG and 4-hydroxy 3-methoxyphenylacetic acid, well known as homovanillic acid (HVA), while performing cognitive tests at rest and during exercise at 40 and 80% maximum power output. Their results suggest a positive relationship between MHPG concentration and cognitive performance; however they did not differentiate sulfate and glucuronide MHPG. Peyrin and collaborators measured urinary sulfate and glucuronide MHPG prior to and following a mental test alone, an exercise bout alone and a combined condition in which participants performed the cognitive tasks while exercising. The three conditions were carried out in different sessions. Peyrin *et al.* showed a positive correlation between cognitive performance in a discrimination test and increases in MHPG sulfate. These two results are very encouraging and further studies measuring plasma MHPG sulfate, while exercising, are needed to test more carefully the catecholaminergic hypothesis.

Contributions of electroencephalography

Electroencephalography (EEG) measures electrical activity produced by the brain as recorded from electrodes placed on the scalp. EEG has a high temporal resolution compared to techniques such as functional magnetic resonance imaging (fMRI) or positron emission tomography (PET); it permits the detection of electrical activity changes in the brain on a millisecond timescale. Recording of EEG requires some methodological precautions, such as removing muscle and eye movement artefacts. Therefore, conducting an experiment which combines exercise and EEG is particularly difficult. In this case, researchers generally prefer cycling rather than treadmill walking or running and post-exercise testing rather than testing during exercise. However, a few authors have made the choice to record EEG concomitantly to exercise (e.g. Pontifex and Hillman, 2007; Yagi *et al.*, 1999). Two approaches with EEG can be found in the literature: (1) the analysis of raw EEG; and (2) the use of summation techniques to analyze evoked potentials (EP) or event-related potentials (ERP). Both approaches have been used to study the effects of exercise on cognition.

Raw EEG can be typically described in terms of rhythmic activity. Most of the cerebral signal observed in the scalp EEG falls in the range of 1–30 Hz. EEG activities below or above this range are generally considered as artifacts. Four frequency bands are distinguished in this range: (1) delta waves (up to 3 Hz) characteristic of slow wave sleep; (2) theta waves (4–7 Hz) observed in drowsiness or meditation states; (3) alpha waves (8–12 Hz), observed when the subject closes his/her eyes or relaxes; and (4) beta waves (12–30 Hz), observed for active or anxious subjects. Several studies assessed the EEG changes induced by acute aerobic exercise. Recordings were carried out either during or following the cessation of exercise. According to the traditional arousal theory (e.g. Duffy, 1962), a decrease in cortical arousal should be evidenced by a shift in power from the faster to the slower frequency bands, whereas an increase in cortical arousal should be evidenced by the opposite tendency (Kubitz and Pothakos, 1997), that is to say, a decrease in alpha activity and an increase in beta activity (Kubitz and Mott, 1996). A meta-analysis conducted by Crabbe and Dishman (2004) reporting 58 effects from 18 studies concluded that compared to before exercise, all frequency bands were increased by one-half a standard deviation during and immediately after exercise. These results do not support either a selective influence of acute exercise on a specific frequency band nor a shift from slower to faster frequency bands induced by physiological arousal. Other physiological phenomena which take place during exercise may also contribute to shifts in EEG frequency bands. For instance, the elevation of core and brain temperature observed during exercise may increase central fatigue and reduce alertness (Rasmussen *et al.*, 2004). Future studies examining the putative mechanisms underpinning the changes in spontaneous EEG activity induced by exercise are required.

The use of the EP/ERP technique seems more promising than the analysis of EEG power spectral densities. EPs and ERPs are electrical positive or negative brain waves time-locked to certain events as stimuli and responses (Picton and Hillyard, 1988). EPs always follow a stimulus whereas ERPs may both precede or follow it. Cognitive psychologists and some neurophysiologists assume that EPs reflect sensory processes elicited by the stimulus whereas ERPs reflect endogenous predictive or reactive cognitive operations involved in information processing. Raw EEG contains background activity which masks EPs/ERPs and represents ongoing brain processes. The use of averaging techniques permits isolation of EPs/ERPs from this background activity. Latency and amplitude of ERP are generally used as indices of cognitive functions or the efficiency of stages of information processing in reaction time protocols. Two ERP components are particularly interesting in the examination of facilitating effects of acute aerobic exercise on cognition, the P300 wave and the contingent negative variation (CNV).

The P300 is a positive wave recorded around 300 ms after the occurrence of the response signal. According to (Polich and Criado, 2006; Polich, 2007), P300 can be separated into two components: (1) P3a reflecting a stimulus-driven frontal attention mechanism during reaction process; and (b) P3b reflecting the allocation of attentional resources for memory updating in temporal and parietal cortices. Brain catecholamines would contribute to the generation of P3a. The CNV is a negative

slow wave that takes place during the foreperiod duration of a reaction time, that is to say, between the warning signal and the response signal. It was first detected by Walter *et al.* (1964) and was separated into two components: (1) an early CNV reflecting an orienting response (e.g. Loveless and Sanford, 1974); and (2) a late component interpreted as indexing motor preparation (e.g. Vidal, Bonnet and Macar, 1995).

If acute aerobic exercise increases arousal and activation, more resources should be available for stimulus-driven attention and motor preparation, and the following hypotheses can be made: (1) P300 and CNV amplitudes should be larger in the exercise than in the rest condition; and (2) P300 latency should be shorter in the exercise than in the rest condition. Seven studies measured P300 during or following exercise (Kamijo *et al.*,2004b, 2007; Magnièe *et al.*, 2000; Grego *et al.*, 2004; Hillman, Snook and Jerome, 2003; Pontifex and Hillman, 2007; Yagi *et al.*, 1999). Six out of seven studies observed an increase in P300 amplitude during (Grego *et al.*, 2004; Pontifex and Hillman, 2007) or following exercise (Hillman, Snook and Jerome, 2003; Magnièe *et al.*, 2000; Kamijo *et al.*, 2004b; Kamijo *et al.*, 2007) by comparison with rest. However, it is important to note that the increase in P300 amplitude was observed only during the first 2 hours of a 3 hour bout of cycling exercise in the Grego *et al.* (2004) study, and only for light- (RPE = 11) and medium-intensity exercises (RPE = 13), but not for high intensity exercise (RPE = 15) in the Kamijo *et al.* (2004a) study. Only one study observed a decrease in P300 amplitude, but this was during a 10 minute moderate intensity cycling exercise (Yagi *et al.*, 1999) and with a speed-accuracy trade-off between rest and exercise in the RT task. For that reason, I did not consider this last study in the review of exercise effect on P300 latency.

Three studies out of six observed a decrease in P300 latency (Hillman, Snook and Jerome, 2003; Kamijo *et al.*, 2007; Magnièe *et al.*, 2000), whereas two out of six observed an increase (Grego *et al.*, 2004; Pontifex and Hillman, 2007). Only one study examined the effect of an acute bout of aerobic exercise on CNV amplitude (Kamijo *et al.*, 2004a). The authors found lower CNV amplitude following high-intensity exercise in comparison to moderate-intensity exercise and rest conditions, but no difference was observed between rest and moderate-intensity exercise. Taken together, these studies confirm the importance of carefully controlling the intensity and duration of exercise in order to obtain facilitating effects of exercise on cognitive processes and neuroelectric mechanisms. More studies are needed to examine the effect of acute bouts of steady-state exercise on ERPs in different cognitive tasks.

Brain imagery techniques such as fMRI, PET and magnetoencephalography (MEG) could also be very useful to examine the effects of acute exercise on cognitive processes. However, these techniques have been only employed to examine the hemodynamical and metabolic adaptations of the human to acute exercise (e.g. Hollman *et al.*, 1994, for a review; see also Chapter 8 of this book) or the effects of chronic bouts of exercise on brain structure or brain functioning, particularly in ageing people (e.g. Colcombe *et al.*, 2004; Colcombe *et al.*, 2006). The use of these brain imagery techniques during cycling exercise would require the elaboration of specific apparatus allowing leg motions without any motion of the head. To my knowledge, such study has not yet been conducted.

1.7 Conclusion

This chapter is an attempt to give useful theoretical and methodological frameworks for researchers interested in the effects of acute bouts of exercise on sensorimotor and cognitive processes. A large set of experimental data led exercise and cognitive neuroscientists to consider that acute aerobic exercise acts like an arousing psychostimulant drug via brain noradrenergic and dopaminergic pathways. In addition, several lines of evidence suggest that increases in arousal and activation induced by exercise do not have a general facilitating effect on cognition but rather a selective influence on specific stages of information processing, such as sensory and motor processes. Some cognitive processes such as executive functions may be impaired by acute aerobic exercise. Future research integrating cognitive and energetic approaches and combining different methodologies presented earlier are needed to elucidate more precisely the neurophysiological mechanisms which underlie the effects of acute exercise on cognition, that is which psychological functions are improved by exercise and which ones are impaired. There is also a need for an innovative and heuristic cognitive-energetic model of exercise and cognition which would take into account data collected since 1995.

2

Exercise and cognitive function: a neuroendocrinological explanation

Terry McMorris

The notion of a neuroendocrinological explanation for the exercise-cognition interaction was first posited by Cooper (1973). It received very little interest or support. Fortunately, not everyone ignored Cooper's claims and the Polish sports scientists Chmura, Nazar and Kaciuba-Uscilko (1994) resurrected his ideas 21 years later. Cooper claimed that there was a link between the release of the catecholamines, adrenaline (often called epinephrine) and noradrenaline (or norepinephrine) into the blood during exercise and increases in the availability of neurotransmitters in the brain. In this chapter, we examine the roles of the catecholamines and 5-hydroxytryptamine (5-HT) which is better known as serotonin, as neurotransmitters in the brain. We also look at the effect of the hormone cortisol on brain activity. More importantly, we discuss the interaction between exercise, the synthesis and release of these neuroendocrines and cognitive functioning. Finally, I present a possible model for such an interaction.

2.1 Catecholamines and 5-hydroxytryptamine as brain neurotransmitters

Noradrenaline, dopamine, 5-HT and, to a much lesser extent, adrenaline act as neurotransmitters in the brain. Once synthesized they are held in vesicles (organelles of ~40 nm in diameter) in the brain and, when released, innervate what have been termed the noradrenergic, dopaminergic and serotonergic pathways (Meeusen and De Meirleir, 1995). The majority of noradrenaline-containing neurons are to be found in the locus coeruleus. Once released, however, they are projected throughout the entire cerebral cortex and the cerebellum. Dopamine-containing cell bodies are

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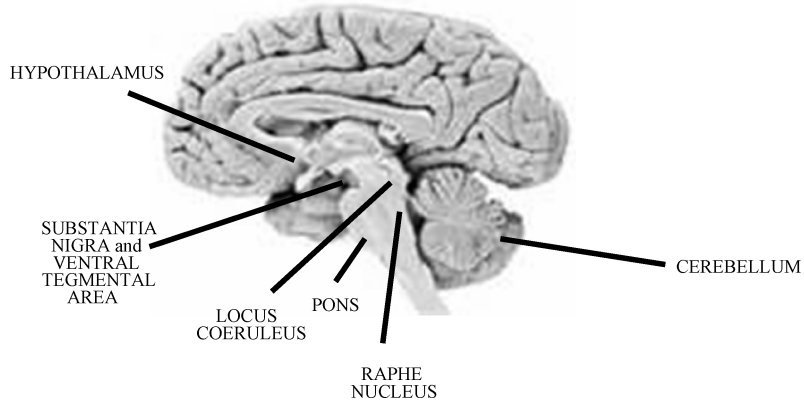

Figure 2.1 Selected areas of the brain that are part of the adrenergic, dopaminergic and serotonergic pathways.

found mainly in the substantia nigra and ventral tegmental areas. Dopamine axons primarily innervate the corpus striatum where 80% of the brain's dopamine is found. Although the neurons containing 5-HT are almost entirely found in the raphe nucleus, their axons innervate nearly every area of the brain. They are strongly represented in the pons, midbrain, amygdala, hippocampus, hypothalamus and thalamus. Intermediate density is found in the cerebellum and cerebellar cortex (Kuhar, Couceyro and Lambert, 1999; Loubinoux *et al.*, 2002) (Figure 2.1).

The small amount of adrenaline found in the brain originates in neurons, which contain phenylethanolamine *N*-methyltransferase (PNMT), in the pons and medulla. The presence of PNMT is necessary for the process of *N*-methylation by which adrenaline is synthesized from noradrenaline. The axons of these neurons terminate mainly in the brainstem and hypothalamus (Kuhar, Couceyro and Lambert, 1999).

Before leaving the noradrenergic, dopaminergic and serotonergic pathways we should briefly explain the role of neural receptors in the brain. Once the neurotransmitters have been released from the vesicles, by a process known as exocytosis, they are taken up by receptors. The main receptors for noradrenaline are called α-adrenergic and β-adrenergic receptors. Both the α- and β-receptors have been broken down into sub-sets based on their chemical make-up. This is not of direct importance to us. Those interested in this area can consult any basic neurochemistry text (some may see the terms 'basic' and 'neurochemistry' as contradictory). Whether the noradrenaline is taken up by the α- or β-receptors is very important. Take-up by the β-receptors stimulates the action of the enzyme adenyl cyclase, which is necessary for the synthesis of a secondary messenger, cyclic adenosinemonophosphate (cAMP). However, take up by the α-receptors inhibits adenyl cyclase activity. The secondary messenger amplifies the effects of neuronal activity. If the secondary messenger is not activated, the resulting negative feedback has a controlling effect on transmitter release (Arnsten, 1997).

Dopamine also has receptors that inhibit and those that stimulate adenyl cyclase activity. Dopamine D1-type receptors stimulate activity, while D2-type are inhibitors. As with the adrenergic receptors, there are sub-groups of these receptors. The naming of these is counter-intuitive, with D5 being part of the D1 group, while D3 and D4 are grouped with D2 (Floresco and Magyar, 2006; El-Ghundi et al., 2007). Similarly, there are inhibitory and stimulating 5-HT receptors. The inhibitory 5-HT_1 receptors work similarly to α-adrenergic and D- type receptors. The stimulatory receptors are not linked to adenyl cyclase activity (Meneses, 1999; Alex and Pehek, 2007). There are several of them and they work differently to one another (see Frazer and Hensler, 1999).

2.2 How exercise induces increases in brain concentrations of noradrenaline, dopamine, cortisol and 5-hydroxytryptamine

The synthesis of catecholamines takes place in chromaffin cells in the brain and depends on the hydrogenation of phenylalanine. This is converted to tyrosine with phenylalanine hydroxylase acting as a catalyst. It is further broken down into the metabolite 3, 4 dihydroxy-L-phenylalanine (L-DOPA) under the influence of tyrosine hydroxylase, which is found in all cells that synthesize catecholamines. L-DOPA is then catalyzed by DOPA decarboxylase and dopamine is formed. With the aid of dopamine-β-hydroxylase, noradrenaline is synthesized. Dopamine and the majority of noradrenaline are stored in vesicles, which are found in many areas of the brain. Some noradrenaline passes into the adrenal medulla where it is *N*-methylated into adrenaline. Adrenaline is then transported back into chromaffin granules for storage (Kuhar, Couceyro and Lambert, 1999) (Figure 2.2).

During, and even immediately before, exercise the hypothalamus and brainstem initiate action of the sympathoadrenal system (SAS), which is part of the autonomic nervous system (ANS). This results in the release of catecholamines at the postganglionic cells of those neurons that require activating or inhibiting. As exercise increases in intensity there is also release of adrenaline and, to a lesser extent, noradrenaline from the adrenal medulla (Figure 2.3). The catecholamines play important roles in the organism's ability to undertake exercise. It is not the purpose of this book to examine these roles, there are many excellent exercise physiology and exercise biochemistry texts that do this, but I will outline the major functions. Adrenaline and, to a lesser extent, noradrenaline play important roles in glycolysis, which allows the individual to utilize glycogen efficiently. Both are also involved in lipolysis, which controls fat metabolism. They also play a part in regulating cardiorespiratory responses to exercise. Dopamine is less involved in physical activity but plays a role in kidney activity (for a fuller explanation see Genuth, 2004).

It has long been thought that there is an interaction between the release of catecholamines into the periphery and increases in brain concentrations. Lacey and

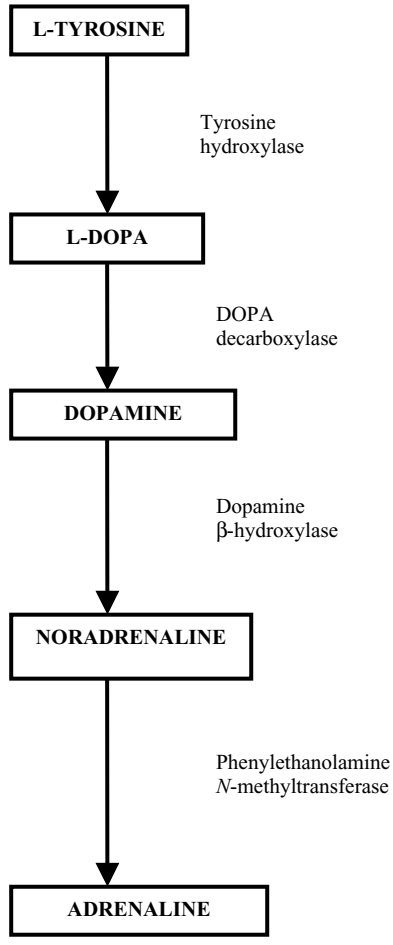

Figure 2.2 Catecholamines synthesis.

Lacey (1970) pointed to the way in which nonphysical stressors resulted in increased plasma concentrations of catecholamines. Perhaps more importantly, early animal studies (Brown and Vanhuss, 1973; McGaugh, 1983) demonstrated increases in brain concentrations of catecholamines during exercise. (We will discuss empirical evidence for an exercise-induced increase in brain catecholamines in the next section.) Genuth (2004) suggests that the release of catecholamines in the periphery triggers some release in the brain and vice versa. However, he points out that this may be a very limited interaction. Probably the most important factor is ANS feedback to the hypothalamus via the thalamus, reticular activation system and limbic system, concerning stress on the cardiorespiratory system, pain and glycogen depletion. This triggers a response by the hypothalamus, which results in increased release of catecholamines peripherally and possibly centrally. It also stimulates action by the hypothalamic-pituitary-adrenal (HPA) axis.

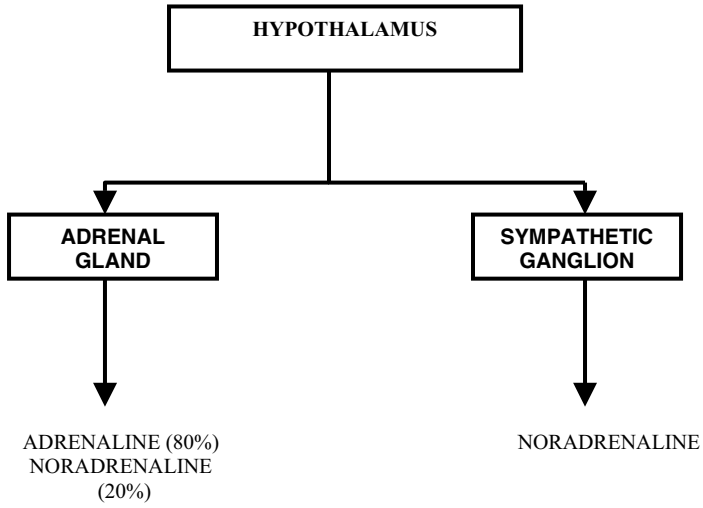

Figure 2.3 Sympathoadrenal system.

Hypothalamic-pituitary-adrenal axis activity

The importance of the hypothalamus in regulating the interaction between body and brain can not be overstated. As we saw above, it coordinates SAS activity. It also coordinates HPA activity. Feedback to the hypothalamus concerning stress, including exercise, sets in motion HPA activity (Figure 2.4). Corticotropin releasing hormone (CRH), often called corticotropin releasing factor, is synthesized in the paraventricular neurons (PVN) of the hypothalamus. It is then secreted into the hypophyseal vessels in the median eminence, where anterior pituitary corticotrophs secrete adrenocorticotropin hormone (ACTH), which is often referred to simply as corticotropin, from its precursor preproopiomelancortin (POMC). ACTH, in turn, passes into the zona fasciculata of the adrenal cortex resulting in the synthesis and secretion of the hormone cortisol (Brandenberger *et al.*, 1980; Genuth, 2004). This hormone plays a major role in the exercise-cognition interaction. Another important secretagogue of cortisol is argenine vasopressin (AVP), also known as antidiuretic hormone (ADH) (Vale *et al.*, 1983). The importance of this hormone in the synthesis of cortisol, when the individual is dehydrated, is discussed in Chapter 5.

During exercise, cortisol plays important roles in glucose production from proteins, facilitates fat metabolism and muscle function, and maintains blood pressure, among other activities (Deuster *et al.*, 1989). Cortisol also regulates the CRH concentrations by blockading hypothalamic release and inhibiting the transcription of POMC into ACTH in the pituitary. However, under high levels of stress, such as prolonged and/or strenuous exercise, this inhibiting effect is impaired. Heavy exercise results in increased concentrations of AVP, in the median eminence, resulting in oversecretion of AVP into pituitary portal circulation. This, in turn, stimulates oversecretion of ACTH, with cortisol being unable to regulate matters even when concentrations are

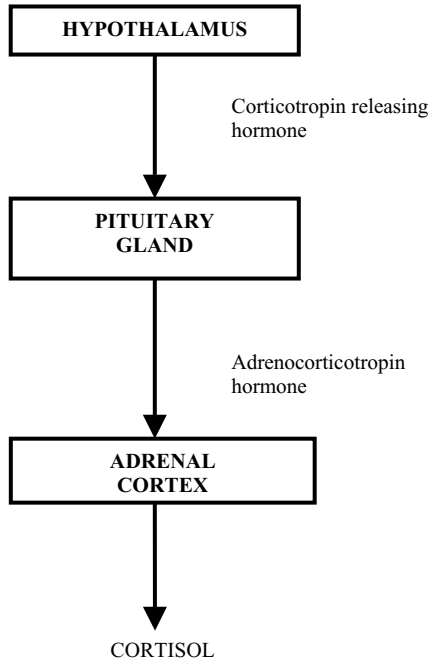

Figure 2.4 Hypothalamic-pituitary-adrenal axis.

very high. (In fact, the interaction between cortisol and ACTH is complex. High concentrations of cortisol can lead to hyposecretion of ACTH but very high concentrations to hypersecretion.) Thus, moderate concentrations of plasma cortisol are indicative of intense but controlled physical activity, while very high concentrations show that the individual is unable to cope (Deuster *et al.*, 1989).

Before leaving HPA activity we should note the interaction between the SAS and HPA systems. Noradrenaline presence results in an increase in CRH synthesis, while increased CRH concentrations lead to an increase in adrenaline synthesis and release. Also, adrenaline stimulates ACTH synthesis in the pituitary. The synthesis and release of catecholamines and cortisol are also affected by the synthesis and release of 5-HT, which we discuss next.

Synthesis and release of 5-hydroxytryptamine

The synthesis of 5-HT begins with the transportation of the amino acid tryptophan from the blood into the brain. Under the influence of tryptophan hydroxylase, 5-hydroxytryptophan is formed. This is further broken down by aromatic L-amino acid decarboxylase (AADC) into 5-HT (Figure 2.5). This process takes place mainly in the raphe nuclei of the brain. This is the only place that 5-hydroxytryptophan is found. 5-HT is stored in vesicles, mainly the parafollicular cells of the thyroid (Meneses, 1999; Lefebvre *et al.*, 2001).

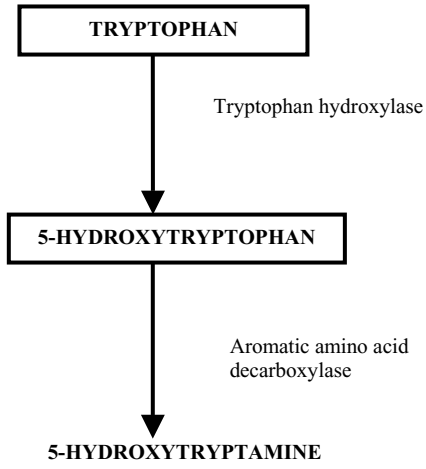

Figure 2.5 5-Hydroxytryptamine synthesis.

Exercise is a particularly good inducer of 5-HT synthesis. Tryptophan, the precursor of 5-HT, is found in plasma either bound to albumin or unbound. Unbound tryptophan readily crosses the blood–brain barrier. During exercise, free fatty acids displace tryptophan from binding with albumin, therefore there is an increase in unbound tryptophan. This crosses into the brain and forms 5-HT (Chaouloff *et al.*, 1986).

The synthesis and presence of 5-HT is related to the synthesis of dopamine as AADC also plays a major role in the conversion of DOPA into dopamine. Whether the presence of AADC leads to the synthesis of dopamine or 5-HT is dependent on blood pH and the presence of concentrations of various substrates (Frazer and Hensler, 1999). The main interaction between 5-HT and other hormones is that with cortisol. 5-HT stimulates the synthesis and secretion of ACTH from the pituitary, CRH in the hypothalamus and cortisol in the adrenal cortex (Alex and Pehek, 2007).

Empirical evidence for exercise-induced changes in brain concentrations of catecholamines, 5-hydroxytryptamine and cortisol

In this section, we discuss empirical evidence for exercise-induced changes in brain concentrations of catecholamines, 5-HT and cortisol. We focus particularly on noradrenaline, dopamine and 5-HT, as adrenaline plays only a small part in brain activity. Exercise is a stressor and will, therefore, affect brain concentrations of catecholamines, 5-HT and cortisol in the same way as any other stressor. However, given the peripheral roles of noradrenaline and dopamine during exercise, it may affect brain concentrations of these catecholamines in a way that other stressors do not. Also, the interaction between exercise and the unbinding of tryptophan could well mean that 5-HT is more readily affected by exercise than by other stressors. Also dehydration, which often occurs during prolonged exercise, induces the synthesis and release of ADH, a secretogue of cortisol. Therefore, we must examine evidence for exercise-induced changes specifically.

The original hypothesis of Cooper (1973), supported by Chmura, Nazar and Kaciuba-Uscilko (1994) and McMorris *et al.* (1999), was that exercise induced increases in brain concentrations of noradrenaline and dopamine, which were then readily available for use in cognitive tasks. The presence of the blood–brain barrier means that if this hypothesis is correct, it can not be a simple effect of peripherally circulating catecholamines entering the brain during exercise. Brain endolethial cells differ from other endolethial cells in that they have tight junctions, which prevent transcapillary movement of molecules. Nor do they contain transendolethial pathways, hence they form a barrier. Without the blood–brain barrier we would be unable to control our emotions. It is essential, however, that some substances can cross the barrier. Crossing is mostly by diffusion and depends on the lipid solubility of the substance. Catecholamines do not readily cross the blood–brain barrier. Only a very small percentage can cross (Oldendorf, 1977; Cornford *et al.*, 1982), therefore increases in plasma concentrations would have to be very high in order to have any effect. Such an effect has been shown with rats (McGaugh, 1983), but the rats exercised at a level that is not viable with humans. Hence the argument that the action of the ANS is the key in examining an interaction between exercise and brain catecholamines concentrations. Obtaining empirical evidence for such an interaction is extremely difficult.

Despite the fact that research showing that psychological stress results in increased plasma concentrations of catecholamines (Sothmann, Hart and Horn, 1991) and that theoretically, SAS release of catecholamines peripherally and centrally may interact (Genuth, 2004), directly testing this with humans is not possible. As a result, researchers have drawn on animal studies to support their claims that exercise induces changes in brain concentrations. Since the early work of McGaugh (1983), methods of measuring brain concentrations of catecholamines and 5-HT during and after exercise have improved dramatically. The biggest improvement has been the use of microdialysis (for a description of this method see Meeusen, et al., 2001).

Animal studies and catecholamines

As adrenaline plays only a small part in brain activity, researchers have focused on noradrenaline and dopamine. For both, results have been far from unequivocal. There appears to be more consistency for dopamine. There is evidence of increased dopamine concentrations during and following acute exercise and as a result of chronic exercise. Research on acute exercise has demonstrated increases particularly in the brainstem and hypothalamus (Meeusen *et al.*, 1996, 2001). Chronic exercise shows region-specific effects with increases in hypothalamus and midbrain concentrations but decreases in prefrontal cortex, hippocampus and striatum (Meeusen *et al.*, 1996, 1997). Moreover, changes during acute exercise only appear to occur when intensity goes above a threshold level (Hattori, Naoi and Nishino, 1994).

The effect of exercise on whole brain concentrations of noradrenaline in animals has been the opposite of that hypothesized by Cooper (1973), Chmura, Nazar and Kaciuba-Uscilko (1994) and McMorris *et al.* (1999). In general, studies have shown

either a decrease or no significant effect, although there are some regional variations. Decreases have been shown in the brainstem, hippocampus, pons medulla, midbrain and hypothalamus but increases in the striatum. On the other hand, chronic exercise has resulted in increased concentrations in the hypothalamus, but whole brain concentrations have been shown to be lowered by training (Meeusen *et al.*, 1997, 2001).

There is, however, unequivocal evidence for an increased catecholamine turnover in the brain during exercise. Increased concentrations of catecholamines metabolites have been found in the brain during and following acute exercise. Metabolites are the by-products of catecholamines synthesis and usage. Increased concentrations of the noradrenaline metabolite 3-methoxy 4-hydroxyphenylglycol (MHPG) have been found in most brain regions (Gerin and Privat, 1998), while increased concentrations of the dopamine metabolites 3,4-dihydroxyphenylacetic acid (DOPAC) and 4-hydroxy 3-methoxyphenylacetic acid or homovanillic acid (HVA) have also been shown, particularly in the brainstem and hypothalamus (Meeusen *et al.*, 1997). As such, it would appear safe to say that exercise induces increased catecholaminergic activity in the brain during activity. However, two major questions remain. Firstly, does the same happen in humans and, secondly, to what extent does this mean that there is an increase in the efficiency of cognitive functioning in the brain?

The increased usage of brain catecholamines found during exercise in animals would appear to be the result of the animal trying to carry out the physical activity. It is possible that some usage was related to the animals' emotional states, however we have no proof of this. The inability of the animals to give a score on the Borg (1973) Rate of Perceived Exertion (RPE) Scale or complete the Perception of Mood State (POMS) Inventory (McNair et al., 1971) definitely has its limitations. More importantly with regard to our area of interest, the animals were not simultaneously undertaking cognitive tests. So, although we know that exercise induces increased brain catecholamines activity, we do not know if exercise facilitates the use of catecholamines in areas of the brain involved in cognition.

Exercise and brain concentrations of 5-hydroxytryptamine

5-HT synthesis is not affected by the blood–brain barrier. As we saw earlier, exercise increases the amount of unbound tryptophan, which readily crosses the blood–brain barrier where it interacts with 5-hydroxytryptophan to produce 5-HT. It is, therefore, of little surprise that animal studies have shown increased whole brain concentrations of 5-HT and also increased concentrations in specific regions, in particular the brainstem, hippocampus and hypothalamus, although there may not be an effect in the cerebral cortex (Meeusen et al., 2001). Increases appear to be time dependent. This is not surprising when we consider that the action of unbinding tryptophan from free fatty acids is a direct effect of the organism's use of fat as the main energy supply. Fats rather than carbohydrates are recruited mostly in sub-maximal, long-duration

exercise. What increases in brain concentrations of 5-HT mean with regards to cognition is discussed later.

2.3 Exercise, catecholamines, cortisol and cognition: research

The first attempt to carry out a systematic examination of the interaction between exercise, plasma catecholamines concentrations and cognition in humans was by Chmura, Nazar and Kaciuba-Uscilko (1994). Participants undertook a two-choice visual reaction time test at rest and during a multistage incremental exercise test to exhaustion. Each stage consisted of 3 mins cycling on an ergometer at 50–60 rpm starting with a workload of 50 W, which was increased by a further 50 W at each incremental stage. There was a 1 min interval between stages. The reaction time test was carried out in the last 2 mins of each stage and plasma adrenaline and noradrenaline samples were taken at the end of each stage.

The relevance of the results found by Chmura, Nazar and Kaciuba-Uscilko (1994) is difficult to evaluate. They report that 'Mean RT (reaction time) values were found to decrease with increments in exercise load until work loads varying between 100 and 300 W were reached. . . At work loads exceeding RT minim. there was a sharp increase of RT' (p. 173). However, the statistical analysis is somewhat strange. The authors do not carry out a one-way analysis of variance (ANOVA) to determine whether or not exercise induced significant changes in reaction time, as one would expect. Rather they isolated each participant's minimum reaction time and, using t-tests, compared this value to that at rest. They found that minimal reaction time was significantly lower. They also compared minimal reaction time to maximum reaction time and showed the latter to be significantly longer. The failure to undertake an omnibus examination, that is ANOVA, increases the chances of a compound error (see Cohen, 1988, for an explanation). An alternative method to the use of ANOVA would be to include the Bonferroni correction factor with the t-tests. Examination of the probabilities found ($p < 0.001$), however, does suggest that significant differences would have been shown even with the correction factor.

Another problem with the statistical treatment is the interaction between reaction time and catecholamines. A posteriori the authors calculated the participant's adrenaline threshold (T_A) and noradrenaline threshold (T_{NA}). Before continuing the discussion of these results, we should explain what T_A and T_{NA} represent. It has been known for some time that when we plot plasma concentrations of adrenaline and noradrenaline against exercise intensity, concentrations rise exponentially (Lehman, Schmid and Keul, 1985) (see Figure 2.6). Green *et al.* (1983) termed the points at which there is a significant rise in concentrations the T_A and the T_{NA}. These points occur when catecholamines are secreted into the blood via the adrenal medulla as well as from postganglionic cells. Although the T_A and the T_{NA} are highly correlated, they do differ between individuals, therefore we use the terms T_A and T_{NA}, rather than combining the two. It would appear that exercise intensity needs to be fairly high

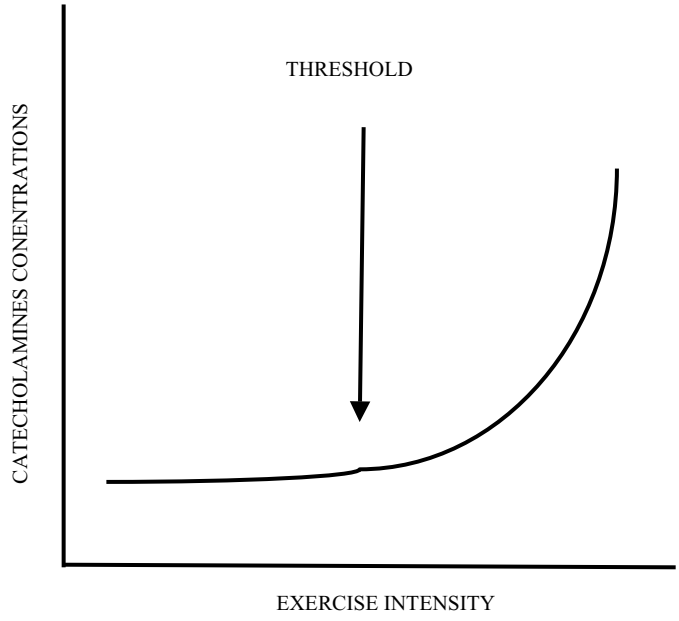

Figure 2.6 Example of catecholamine threshold.

before this occurs but there are large inter-individual variations. It is generally thought that intensity needs to be about 70 + % maximum power output ($\dot{W}_{MAX}$) or 75 + % maximum volume of oxygen uptake (VO_{2MAX}) (Podolin, Munger and Mazzeo, 1991). However, in our research we have shown T_A levels to vary from 40% $\dot{W}_{MAX}$ to 80% $\dot{W}_{MAX}$. The fitter the individual, the higher the threshold. (The $\dot{W}_{MAX}$ test used by researchers in this area is one in which resistance, on a cycle ergometer, is increased every minute until the individual cannot maintain the required pedal rate. The power output at this point is the $\dot{W}_{MAX}$. The VO_{2MAX} tests used have varied somewhat but the definition of VO_{2MAX} is the 'maximum energy output by aerobic processes' [Åstrand and Rodahl, 1977, p.318]).

Returning to the Chmura, Nazar and Kaciuba-Uscilko (1994) study, the authors calculated the workload at which each individual reached their T_A and T_{NA} and examined the relationships between these and the workloads at which they produced their shortest reaction time. Shortest reaction times were at workloads which were significantly higher than the person's T_A and T_{NA}. Although I am not happy about such treatment, as it is turning a dependent variable into an independent one, I think that this was, and still is, an important result. At the very least it suggests a prima facie case for an interaction between plasma catecholamines concentrations and cognitive performance.

As a follow up to the Chmura, Nazar and Kaciuba-Uscilko (1994) experiment, McMorris *et al.* (1999) examined soccer players on a soccer-specific, decision-making test at rest and during exercise at T_A and at $\dot{W}_{MAX}$. They determined T_A and $\dot{W}_{MAX}$ in a pre-test and assumed that there would be no significant differences in

percent $\dot{W}_{MAX}$ at T_A, or indeed in $\dot{W}_{MAX}$ itself, between the pre-test and the actual test. While it is very unlikely that there would have been any differences for fit participants who were not undertaking training at the time of the tests, it is a weakness in design which may have affected results. T_A was determined by the log-log method of Beaver, Wasserman and Whipp (1985) but there were relatively few blood collection points from which to determine the threshold. This could have affected the calculation. It should be pointed out that T_A was found to occur at 56.78% (SD = 12.9) $\dot{W}_{MAX}$, which is comparatively low. Given that the $\dot{W}_{MAX}$ of the subjects were not low, this is probably more due to the method of calculation than fitness level. Despite this, the authors found a significant improvement in speed of decision at T_A and that this was maintained during $\dot{W}_{MAX}$, the latter result being very different to that found by Chmura *et al.* Accuracy of decision was not affected. Unfortunately the authors did not carry out any correlations between plasma adrenaline concentrations and cognitive performance. Moreover, although they also determined the T_{NA} this was not used in any analyses. T_{NA} also occurred at a comparatively low $\dot{W}_{MAX}$ percentage, 61.20% (SD = 10.6). (Reasons for the difference in speed and accuracy of decision results are discussed in Chapter 9).

McMorris *et al.* (2000) also examined the effect of exercise at T_A and $\dot{W}_{MAX}$, but this time on the performance of a soccer-specific, psychomotor task. T_A and $\dot{W}_{MAX}$ were determined in the same manner as by McMorris *et al.* (1999). However, the task differed significantly. Participants were shown a video of three attackers, each marked by a defender. The attackers were on the right, centre and left of the screen. On a signal, the attackers attempted to get free from their marker. Only one attacker was successful each time (see Chapter 9 for a discussion of this test). The participant had to decide which attacker had freed himself, as quickly and accurately as possible. Participants stood on a reaction timer pad. Once they had made a decision they said right, left or centre and their voice reaction time was measured. Simultaneously, they moved off the pad and kicked a soccer ball at a target. Whole-body reaction time, and absolute, constant and variable error on the kicking aspect of the task were measured. Participants were tested at rest and following exercise at T_A and $\dot{W}_{MAX}$.

There were no significant effects for any of the variables. With regard to the reaction time variables, the authors concluded that the way in which they undertook the test may have affected results. Although participants dismounted the cycle ergometer at T_A and $\dot{W}_{MAX}$ respectively, it took time, albeit < 20 s, to get to the starting position and the test lasted for a mean of 2.33 min (SD = 0.51), with only a limited amount of activity – kicking the ball from a standing position. Given that the half-life of adrenaline is $\leq$ 3 mins, it is unlikely that the participants were at the levels of arousal that the authors had intended. However, one would have expected that in the $\dot{W}_{MAX}$ condition, they would have been still above T_A concentrations, although, Kjaer (1989) has shown as much as 35% reduction in adrenaline concentrations in 1 min. Noradrenaline was not measured in this experiment.

McMorris *et al.* (2000) also claimed that it was possible that the cognitive variables in their task may have been too simple. Simply observing which player freed himself and reacting as fast as possible is an information-transfer task and so

may not be negatively affected by exercise. They also felt that the soccer decision-making task used previously (McMorris *et al.*, 1999) may have been too simple for soccer players, for whom the decision-making was automatic, as shown by the lack of an effect on accuracy (see Chapter 9 for a discussion on this). Therefore, in a further experiment, McMorris *et al.* (2003) decided to examine performance at 70 and 100% $\dot{W}_{MAX}$ on a noncompatible choice response-time task. They also carried out regression correlations using adrenaline and noradrenaline concentrations as the independent variables, and reaction and movement times as the dependent variables.

In the cognitive, noncompatible choice response time test, participants depressed a lever, which was on the handlebars of a cycle ergometer. They viewed a display which had four lights, numbered one to four, and four buttons, one under each light. These buttons were also numbered one to four. When light one was illuminated participants had to press button three; when light two was illuminated they had to press button four; when light three was illuminated they had to press button one; and when light four was illuminated they had to press button two. There were two dependent variables, reaction time and movement time. Reaction time was measured from the illumination of the light to the individual releasing the lever. Movement time was from the release of the lever to the depression of the button. This test was chosen because it requires not only perception of the stimulus but also that the participant must hold information in short-term memory. It could be argued that it is a prefrontal cortex task and, therefore, more likely to be disrupted by stress (Drevets *et al.*, 1995). Movement time at $\dot{W}_{MAX}$ was significantly faster than in the other two conditions. There were no other significant results. Neither adrenaline nor noradrenaline correlated significantly with cognitive performance, although power output demonstrated a significant linear regression with movement time ($R^2 = 0.24$).

In a very recent study (McMorris *et al.*, 2008b), we examined plasma concentrations of adrenaline, noradrenaline, cortisol and ACTH during exercise at 50% $\dot{W}_{MAX}$ and 80% $\dot{W}_{MAX}$, while simultaneously undertaking a cognitive task. The study is reported in more detail below, so here I will only report those results pertaining to catecholamines concentrations. As one would expect, post-exercise adrenaline and noradrenaline concentrations increased linearly from rest to 80% $\dot{W}_{MAX}$ intensity. However, we also examined concentrations pre-exercise, which, in both conditions, were much higher than baseline. Interestingly for noradrenaline, a large pre/post rise in concentrations was only seen in the 80% condition, while adrenaline demonstrated such an effect at both 50 and 80% $\dot{W}_{MAX}$.

The cognitive task used was the flanker task (Eriksen and Eriksen, 1974). The effect of exercise was significant for both error and reaction time, with an inverted-U effect being shown for reaction time and a linear decrease in performance for error. A series of regression analyses, with post-test changes from the at rest condition (Δ) for plasma concentrations of cortisol, ACTH and catecholamines as the independent variables and Δ reaction time and Δ error as separate dependent variables, were carried out. A significant correlation between Δ noradrenaline and Δ error ($R^2 = 0.40$) was shown. In

order to fully understand the meaning of these results, one needs to examine the full findings of the study, which are reported later.

Anaerobic exercise research

Despite the fact that most team games require short, fast bursts of anaerobic exercise intermingled with the player making complex decisions, very few studies have attempted to examine the effect of anaerobic exercise on cognitive function and only one has taken a neuroendocrinological approach. Winter *et al.* (2007) examined the effect of aerobic exercise (lactate concentrations $< 2\ \text{mmol}\,\text{l}^{-1}$) and high intensity, repeated sprints (lactate concentrations $> 10\ \text{mmol}\,\text{l}^{-1}$) on a vocabulary learning task and plasma concentrations of dopamine, adrenaline and noradrenaline. Testing took place 15 mins after rest and exercise at each intensity. Testing was undertaken in five blocks.

Accuracy of learning showed a quadratic effect for both high intensity anaerobic and sub-maximal, aerobic running. Speed of learning showed a significant main effect for condition, with anaerobic running inducing faster times than at rest and following aerobic exercise. Dopamine concentrations did not differ between groups. Adrenaline and noradrenaline concentrations showed an increase in the anaerobic condition. There was a low to moderate ($r = 0.46$, $p < 0.02$) correlation between dopamine and speed of learning.

Long duration exercise research

The interaction between long duration exercise, cognition and catecholamines has received little attention. Chmura *et al.* (1998) divided participants into two groups. One group exercised at a workload that meant that the person was exercising at 10% above their lactate threshold (T_{LA}) for 20 mins. T_{LA} and the catecholamines thresholds are closely related (Podolin, Munger and Mazzeo, 1991). The second group exercised for 60 mins at 75% of the workload required to elicit T_{LA}. For the group exercising above T_{LA}, reaction time was examined every 5 mins and for the other group every 10 mins. For the 75% T_{LA} group, choice reaction time significantly decreased linearly from rest to 40 mins and then stabilized at a level significantly lower than that at rest. The above T_{LA} group demonstrated significant improvements from 10 mins onwards. Significant correlations were found between choice reaction time and plasma concentrations of adrenaline ($r = -0.65$) and noradrenaline ($r = -0.68$) for the above T_{LA} group only. Once again there were design problems. Habituations were only 5–7 trials and the statistical analysis between reaction times was by a series of Wilcoxon tests with no correction factor, hence the possibility of a compound error.

Hypothalamic-pituitary-adrenal axis research

Like Chmura *et al.* (1998), Grego *et al.* (2004) also examined the effect of long duration exercise on cognitive performance and plasma catecholamines concentra-

tions. However, they included examination of HPA activity by measuring the effect on serum concentrations of cortisol. Participants undertook a 180 min ride on a cycle ergometer, with a resistance aimed to elicit an exercise intensity of '~66% VO_{2MAX} (181 ± 33 W)' (p. 77). Performance on the cognitive task, using the classic auditory oddball procedure, was measured at rest and during exercise in the 3rd, 36th, 72nd, 108th and 144th min as well as immediately post-exercise and 15 min after cessation of exercise. The auditory oddball task requires the participant to distinguish between an auditory target and a distractor. Event related potentials were measured using P300 latency and amplitude as dependent variables. P300 latency refers to the speed of information processing, while P300 amplitude is a measure of the amount of processing. Participants also undertook a control condition where the same procedure was carried out but without cycling. Venous blood samples were taken before measurement on the oddball tests. Plasma concentrations of adrenaline and noradrenaline and serum concentrations of cortisol were measured.

The authors report that P300 amplitude was significantly larger at the 72nd and 108th min when compared to the 36th min. P300 latency was higher during the 108th and 144th min compared to the 36th min. There were no pre/post-exercise differences. However, the authors do not appear to have undertaken any inferential statistics to compare the control condition with the exercise condition. There were increases after the 108th min in adrenaline and cortisol concentrations; noradrenaline was not affected. There were no correlations between P300 latency and amplitude, and concentrations of catecholamines and cortisol. Despite this last finding the authors claimed that they had provided evidence for a relationship between adrenaline and cortisol concentrations and cognitive performance, because changes in P300 latency and amplitude occurred at about the same time as increases in adrenaline and cortisol concentrations. This appears to be somewhat disingenuous.

As stated earlier, McMorris *et al.* (2008b) examined the effect of exercise at 50 and 80% $\dot{W}_{MAX}$, while simultaneously undertaking a cognitive task, on plasma concentrations of cortisol, ACTH, adrenaline and noradrenaline. The HPA hormones did not demonstrate exactly the same effects as the catecholamines. As with the catecholamines, there were pre/post exercise $\times$ exercise intensity interaction effects, however observation of post hoc data shows different effects. Cortisol concentrations showed little change throughout. ACTH demonstrated very small pre/post differences at rest and 50% $\dot{W}_{MAX}$ but a large pre/post increase at 80%. The fact that cortisol and ACTH activity do not mirror one another is not surprising. Cortisol has a slower diffusion rate than ACTH (Deuster *et al.*, 1989), therefore plasma concentrations of the two will not be indicative of central concentrations at exactly the same time. As stated earlier, under stress, cortisol can inhibit ACTH synthesis, which would also result in differences in amounts of change. However, post-exercise ACTH at 80% $\dot{W}_{MAX}$ showed a very high increase in concentrations compared to the other conditions, while increases in cortisol concentrations were relatively small. Therefore, it is more likely that the increases in ACTH concentrations at 80% are better indicators of stress, at that specific point in time, than are the cortisol concentrations.

The regression analyses with Δ plasma concentrations of cortisol, ACTH, adrenaline and noradrenaline as the independent variables and Δ response time and Δ error on the flanker test as separate dependent variables also show some interesting data. There were no significant correlations at 50% $\dot{W}_{MAX}$. This is not surprising when we note that changes from the at rest condition to the 50% exercise condition, for both response time and error, are minimal. At 80%, there was a significant regression correlation between Δ noradrenaline and Δ error ($R^2 = 0.40$). This suggests a relationship between increases in arousal and increased error. Not a surprising result.

With Δ response time as the dependent variable, Δ adrenaline and Δ ACTH combined demonstrated a significant correlation ($R^2 = 0.29$). Examination of the standardized β coefficients showed that the relationship, for both variables, was an inverted one, meaning that the smaller the increase in adrenaline and ACTH, the greater the increase in response time. This was a little surprising to us. If ACTH and adrenaline concentrations are indicative of increases in stress and arousal, we would have expected greater increases to be related to over-arousal and hence poorer performance. In making sense of these data, we must keep in mind the fact that even the smaller Δ values still represent increases in ACTH and adrenaline concentrations. Similarly, the smaller Δ response times also represent slower performance compared to at rest. So it appears that the interaction between relatively small increases in ACTH and adrenaline plasma concentrations are indicative of comparatively large increases in response tines, while larger increases are related to comparatively smaller increases in response times.

A possible explanation for these data lies in the nature of the protocol for the flanker test. Subjects sat on a cycle ergometer, with a response button on each of the handle grips, facing a computer screen. They were instructed to press the right-hand side button when the letters H or K were presented centrally and the left button when S or C were presented. Noise letters were also presented either side of the stimulus or target button. These could be the same as the target letter, different to the letter but representing the pressing of the same button (e.g. stimulus H and noise K) or different to the stimulus letter and representing the pressing of the other button (e.g. stimulus H but noise S). The problem for the subject was to process information concerning the target or stimulus letter and inhibit responses to the noise letter. However, the response is motoric in nature and requires a simple movement, hence little processing is required.

Thus performance of the test is dependent on central processing, which is complex and has been shown to activate the prefrontal cortex and, in particular, the anterior cingulate cortex (Frith *et al.*, 1991; Paus *et al.*, 1998), and a motor response. As we have seen, prefrontal cortex tasks are particularly susceptible to increases in stress (Jahanshahi and Dirnberger, 1999; Vedhara *et al.*, 2000). Thus, one would expect that individuals demonstrating large increases in adrenaline and ACTH concentrations would show a large increase in the time taken to process the information. However, previous research has shown decreases in motor time in such situations (Davranche *et al.*, 2005a, 2005b). Therefore, one would expect those demonstrating large increases in adrenaline and ACTH concentrations to show decreases in the

motor time aspect of the task. As a result, the slower central processing is, to some extent, off-set by faster motor time resulting in a smaller increase in reaction time for these individuals than for those showing less of an increase in plasma concentrations of adrenaline and ACTH. These individuals will also show negative effects of central processing, albeit less than those with high increases in concentrations, but will not have the advantage of these slower times being off-set by decrease in motor time. Obviously one must proceed with caution when examining this explanation as no separate measures of central activity or motor time were taken. Future research should examine fractionated reaction time in order to further investigate the above claims.

Metabolites research

One of the criticisms of the research has been that the authors assumed that changes in plasma concentrations of catecholamines are indicative of changes in brain concentrations. This, however, ignores the effects of the blood–brain and cerebrospinal fluid (CSF) barriers. The first to attempt to overcome the problem of the blood–brain barrier were Peyrin *et al.* (1987). (It is interesting to note that this study was undertaken seven years before any examination of plasma catecholamines, and exercise and cognition) They examined word discrimination, short-term memory and solving simple arithmetical problems in a control condition and during one hour of cycling at 70% VO_{2MAX}. They found no significant effect of cycling on short-term memory and the arithmetical test but word discrimination was significantly better during exercise. The most important aspect of the Peyrin *et al.* experiment, however, concerned the measurement of catecholamines and their metabolites.

Peyrin *et al.* (1987) examined urinary samples of adrenaline, noradrenaline, metanephrine, normetanephrine and dopamine following an exercise plus cognition condition and in an exercise only condition. Metanephrine and normetanephrine are metabolites of adrenaline and noradrenaline respectively. Sulfate MHPG and free + glucoronide MHPG were also examined. The results are not reported in a way that one would expect today but the authors concluded that 'when compared to exercise alone, combined exercise and mental load' (p. 189) resulted in significant increases of adrenaline and metanephrine combined, and sulfate MHPG. Moreover, during exercise, positive correlations were found between performance on the word discrimination test and Δ concentrations of sulfate MHPG ($r = 0.63$), and adrenaline and metanephrine combined ($r = 0.61$). Interestingly, there were no significant correlations at rest.

McMorris *et al.* (2008a) developed the Peyrin *et al.* (1987) experiment by comparing changes in plasma concentrations of MHPG and HVA in an exercise only condition with those in an exercise plus cognition condition. This is similar to the Peyrin *et al.* (1987) experiment except that HVA was also examined and plasma concentrations were used rather than urine samples. McMorris *et al.* (2008a) argued that any differences between the two conditions could only be due to central activity, as the exercise intensities remained the same, therefore peripherally induced changes

in MHPG and HVA concentrations would be the same in each condition. If the catecholamines hypothesis is correct they should have shown greater Δ concentrations of MHPG and HVA in the exercise plus cognition condition compared to those in the exercise only condition. If the hypothesis is incorrect, they would not see any differences.

In the exercise plus cognition condition, participants' reaction, movement and total response times, and performance on a random number generation test (Baddeley *et al.*, 1998) were examined at rest and during exercise at 40 and 80% $\dot{W}_{MAX}$. The exercise only condition was identical except that no cognitive tests were undertaken. These percentages were chosen as 40% is considered to be below the T_{NA} for moderately fit individuals, while 80% is above for all but the very fittest individuals (Podolin, Munger and Mazzeo, 1991). The random number generation task is a test of working memory (see next section for a description of working memory).

There were no significant effects of exercise on random number generation. Reaction time demonstrated a significant increase at 80% $\dot{W}_{MAX}$, while movement time showed the opposite. The Δ MHPG results demonstrated a significant main effect for exercise intensity, with higher concentrations during exercise at 80% $\dot{W}_{MAX}$, but no significant interaction effect. There were no significant effects for Δ HVA. Regression correlations showed that Δ MHPG and HVA concentrations combined were a strong predictor of Δ random number generation performance, movement time and total response time.

The use of plasma concentrations of MHPG as indicative of brain usage in this experiment may be deemed by some to be controversial. The authors argued that they are better than urinary samples, as Peyrin (1990) claimed that urinary MHPG concentrations are not good indicators of brain activity. Tsuji *et al.* (1986) stated that plasma concentrations of MHPG are better indicators than urinary concentrations of the use of noradrenaline in the brain. Moreover, the relationship between plasma concentrations of MHPG and concentrations in CSF have been found to be high (Stuerenburg and Kunze, 1998). CSF concentrations of MHPG have been shown to be affected by cognitive performance (Wolkowitz, 1994). The use of plasma HVA concentrations is less contentious. Several authors have demonstrated significant correlations between plasma HVA concentrations and cognitive performance (Di Rocco *et al.*, 2000). Moreover, central and plasma concentrations of HVA have been shown to be related (Bacopoulos *et al.*, 1980), although this has not been unequivocally demonstrated (Elsworth *et al.*, 1987).

Chronic exercise

Little research has examined the effect of chronic exercise on cognition from a neuroendocrinological perspective. Blaney *et al.* (1990) compared the effects of undertaking a modified Stroop colour test (Sothmann *et al.*, 1988) on plasma concentrations of ACTH and cortisol in active (mean VO_{2MAX} 68.6 [SD 7.1] ml kg^{-1} min^{-1}) and sedentary (mean VO_{2MAX} 44.7 [SD 4.6] ml kg^{-1} min^{-1}) individuals. There

were no significant effects on ACTH or cortisol concentrations for either group. In a second experiment a group of sedentary individuals undertook a four month training programme, which resulted in an 18% improvement in VO_{2MAX}. When their performance on the Stroop test was compared to a control group no differences were found. Again there were no effects on ACTH or cortisol.

Sothmann, Hart and Horn (1992) examined the effect of a 16 week training session on the performance on the modified Stroop colour test (Sothmann *et al.*, 1988), premotor and motor time on a reaction time test and plasma catecholamines concentrations of a group of sedentary males (mean pre-treatment VO_{2MAX} 35 [SD 1.00] $ml\,kg^{-1}\,min^{-1}$ and mean post-treatment VO_{2MAX} 42 [SD 2.00] $ml\,kg^{-1}\,min^{-1}$). Their performances pre- and post-treatment were compared to those of a control group (mean pre-treatment VO_{2MAX} 33 [SD 2.00] $ml\,kg^{-1}\,min^{-1}$ and mean post-treatment VO_{2MAX} 35 [SD 2.00] $ml\,kg^{-1}\,min^{-1}$). There were no significant effects for any variable, including catecholamines concentrations.

Summary

Observation of research findings concerning the interaction between chronic exercise and cognition suggest that a neuroendocrinological explanation cannot be given. However, the situation concerning acute exercise is somewhat equivocal. Overall comparative data provide only limited support for the hypothesis that exercise-induced increases in catecholamines result in changes in cognitive function. However, regression data suggest some interaction effect. Whether this is cause and effect or not has yet to be shown. The theoretical rationale appears to be strong but the empirical evidence does not fully support it. One possible reason is the use of different types of task in the research. The possibility that simple and complex tasks may be affected differently can not be ignored. We explore this in the next section.

2.4 Task type

The first researchers to examine the interaction between exercise, catecholamines and cognition (Chmura, Nazar and Kaciuba-Uscilko, 1994) used visual choice reaction time as the cognitive variable. Later research has examined decision-making in soccer (McMorris *et al.*, 1999), noncompatible choice reaction time (McMorris *et al.*, 2003), flanker test (McMorris *et al.*, 2008b), random number generation (McMorris *et al.*, 2008a), the learning of a complex task (Winter *et al.*, 2007) and the Stroop colour test (Blaney *et al.*, 1990).

Reaction time

Based on information processing theory (see Welford, 1968), many researchers have claimed that the efficiency of the individual's ability to process information is best examined by the use of reaction time tasks. Reaction time is the time from the onset of

a stimulus to the *beginning* of an overt response. According to information processing theorists, this involves the whole cognitive process from initial perception of a stimulus through decision-making to the efferent organization of a response (Welford, 1968). Closer examination of the task, however, shows it to be comparatively simple. Classical visual choice reaction time tasks involve the participant sitting in front of a display which contains a series of lights. Below each light there is a button. When the participant sees a light illuminated, they must press the button immediately below that light as quickly a possible. Reaction time is measured from the illumination of the light to the pressing of the button. (This is actually more correctly described as a response time task. Reaction time is from illumination of the light up to the point of initiation of the button press and does not include the actual time to press the button. In practice, it is generally classed as reaction time as the movement is extremely small. The term response time is normally used when the distance to be moved is of a greater amplitude than a simple finger press.) Readers should note that many researchers use the term reaction time when referring to speed of decision in working memory tasks. This can be very confusing.

Visual reaction time has been broken down into reception time, the time taken for the visual information to pass from the eyes to the primary visual cortex, opto-motor integration time, the time for the individual to perceive which light is illuminated and to organize the motor response and motor outflow time, the time taken from organization to initiation of action. Although this may sound complex, in fact it is not. Humphreys and Revelle (1984) labelled such tasks 'information transfer' tasks, as they simply require the individual to recognize the presence of a stimulus and then produce a pre-determined response. These tasks activate the basal ganglia, lateral premotor cortex, cerebellum and parietal lobe (Critchley *et al.*, 2003; Rektor *et al.*, 2003). Given that noradrenaline and dopamine are the main neurotransmitters activating these areas of the brain (Rihet *et al.*, 2002; Critchley *et al.*, 2003), it is not surprising to find that research has shown an inter-relationship between these catecholamines and reaction time performance (Robbins, 2002).

Working memory

The other tasks examined by researchers can be broadly described as working memory tasks or at least as being involved in working memory, for example short-term memory (Baddeley, 1986). Baddeley sees working memory as involving perception of the display, holding the necessary information in short-term memory, comparing the present situation with similar past experiences held in long-term memory and, from this comparison, making a decision. He divides working memory into three separate but inter-dependent parts: the central executive mechanism, the phonological loop and the visuospatial sketchpad. The phonological loop is responsible for the encoding of acoustic and verbal information. The visuospatial sketchpad has the same role as the phonological loop except that it processes visual and visuospatial information. The role of the central executive is to oversee and control the whole process. Thus, the visuospatial sketch pad and the phonological loop are

responsible for holding visual and verbal information, respectively, in short-term memory.

The prefrontal cortex is mainly responsible for central executive performance (e.g. Barbas, 2000; Critchley *et al.*, 2003; Seamans, Nogueira and Lavin, 2003). However, there is evidence that many other parts of the brain are involved (Chudasama, Bussey and Muir, 2001; Critchley *et al.*, 2003). It seems that the prefrontal cortex (PFC) is particularly responsible for recalling past experience from long-term memory and the integration of that information with perception of the present situation. The long-term memory information is probably held permanently in the post-sensory regions of the temporal and parietal cortices. These areas are known to have strong connections with the prefrontal cortex (Gazzaniga et al., 2001). It would appear that the phonological loop involves the lateral frontal and interior parietal lobes of the left hemisphere. The visuospatial loop seems to be situated in the parieto-occipital region of both hemispheres, although it is more active in the right hemisphere (Barbas, 2000). The basal ganglia are known to play a major role in short-term memory processes and to combine with the dorsolateral prefrontal cortex (DLPFC) in central executive tasks (Frith *et al.*, 1991). These areas are also activated by the noradrenergic and dopaminergic pathways (Luciana et al., 1998; Chamberlain *et al.*, 2006) (Figure 2.7).

Learning

Very recent research by Winter *et al.* (2007) has examined the effect of exercise on learning. The prefrontal cortex is generally thought to play a major role in learning (Ramos and Arnsten, 2007) but the key area for consolidation of memory is the

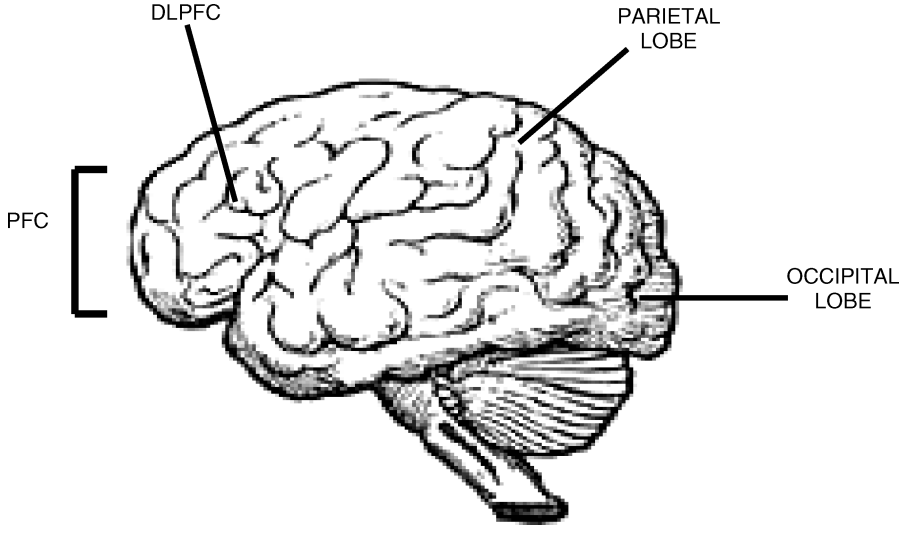

Figure 2.7 Parts of the brain involved in working memory. PFC: prefrontal cortex; DLPFC: dorsolateral prefrontal cortex.

hippocampus. It will be of little surprise to readers to find that both noradrenaline and dopamine are major neurotransmitters activating the hippocampus. Moreover, the hippocampus is positively affected by moderate increases in arousal, therefore one would expect moderate intensity exercise to have a positive effect. During high levels of arousal, however, increases in cortisol concentrations are known to have a negative effect on hippocampal activity (Hopper *et al.*, 2004). Therefore, one would expect learning to be negatively affected during heavy exercise.

As well as measuring catecholamines, Winter *et al.* (2007) examined changes in serum concentrations of brain derived neurotrophic factor (BDNF). In the brain, BDNF is a key factor in the growth and survival of cholinergic neurons in the forebrain, dopaminergic neurons in the striatum and retinal ganglion cells, and some motor neurons. Winter *et al.* examined BDNF because it is known to play an important role in memory (Cotman and Engesser-Cesar, 2002) and animal studies have shown an effect of exercise on concentrations in the hippocampus (Berchtold *et al.*, 2005), which is vital for the consolidation of memory. However, although exercise induced the expected increase in serum BDNF concentrations, there were only limited correlations with cognitive performance. Winter *et al.* reported that 'the more sustained the BDNF levels during learning (BDNF levels after learning minus BDNF levels after exercise), the greater the immediate learning success. . .for the "intense" condition ($r = 0.38$, $p = 0.05$' (pp. 604–605). This is not too surprising as BDNF is involved in the activity of other neurotransmitters. BDNF can stimulate the release of neurotransmitters from pre-synaptic nerve cells and can itself be synthesized following stimulation due to synaptic activity. It is, therefore, impossible to tell what exactly is the cause for increased BDNF concentrations. We do know, however, that BDNF is synthesized by sensory neurons, thus suggesting an interaction with exercise.

Later, in a performance rather than a learning study, Ferris, Williams and Shen (2007) also examined exercise, cognition and serum BDNF concentrations. They found improvements in performance on a Stroop colour test during exercise at 20% below ventilatory threshold and 10% above the threshold. However, BDNF only showed a significant increase at 10% above the threshold. Although BDNF readily crosses the blood–brain barrier and is stimulated by exercise, it is not possible at this moment in time to talk about cause and effect activity with regard to exercise and cognitive function.

Summary

From the information provided above, we might expect that the reaction time and working memory tasks would be equally affected by exercise as both are dependent on the noradrenergic and dopaminergic pathways and are affected by the serotonergic pathway. However, it is generally thought that working memory tasks require more activation and are therefore more susceptible to disruption from any stressor (Drevets *et al.*, 1995). The working memory tasks used in the studies reviewed above have tended to show a positive effect (Peyrin *et al.*, 1987; McMorris *et al.*, 1999;

Grego *et al.*, 2004; Winter *et al.*, 2007) but not unequivocally (McMorris *et al.*, 2008a; 2008b). However, in those studies that have examined regression correlations between plasma concentrations of catecholamines and/or their metabolites, significant correlations have been shown (Peyrin *et al.*, 1987; McMorris *et al.*, 2008a). It should be noted that the McMorris *et al.* (1999) test may, in fact, have been more of a reaction time test than a working memory test as the response may have been automated for experienced footballers (see Chapter 9 for a discussion of this). The reaction and response time tasks results are more equivocal. Moreover, Chmura, Nazar and Kaciuba-Uscilko (1994) demonstrated significant positive correlations between reaction time and catecholamines concentrations while McMorris *et al.* (2000) did not. Thus, the situation is somewhat unclear and probably cannot be explained merely by task type. Other factors must also be affecting results. We discuss these in the next section.

2.5 Discussion

The empirical evidence for a neuroendocrinological rationale for an acute exercise-cognitive function interaction is weak but the theoretical rationale is strong. Why this may be the case is examined in the final section of this chapter. Theoretically, given the roles of noradrenaline and dopamine in reaction time and working memory tasks, the hypothesis that exercise-induced increases in brain concentrations of these neurotransmitters would result in improved performance of such tasks has intuitive appeal. However, the situation is not as simple as that. Noradrenaline and dopamine are also the main neurotransmitters for the premotor cortex and supplementary motor areas, which control movement. So not all of the noradrenaline and dopamine can be allocated to the prefrontal cortex, basal ganglia and related areas, when cognition takes place during the physical activity. The situation is further complicated by the fact that exercise is a stressor, as most readers will not need reminding. During stress the limbic system, and in particular the amygdala, is activated. The main neurotransmitters involved are noradrenaline, dopamine and 5-HT, while cortisol plays a major role in controlling neurotransmitter activity. Activation of the limbic system, however, can have two different effects. Research has shown that moderate increases in limbic system activation are related to improved cognition due to increased arousal (Nielson and Powless, 2007). However, as the amygdala is further activated there is a negative effect (Roozendaal *et al.*, 2006).

The empirical data reported above do not unequivocally support an interaction between endocrinal responses to acute exercise and cognition. Studies have demonstrated significant improvements in cognition occurring at the same time that there are significant increases in plasma concentrations of adrenaline and noradrenaline (Chmura, Nazar and Kaciuba-Uscilko, 1994; McMorris *et al.*, 1999). As we have seen, however, the statistical analyses of Chmura, Nazar and Kaciuba-Uscilko (1994) and the way in which McMorris *et al.* (1999) calculated T_A and T_{NA} cast some doubt over the findings of those studies. Moreover, McMorris *et al.* (2003) failed to show a

significant change in cognitive performance following T_{NA}. Several other studies have failed to find significant improvements in cognition at workloads that are considered to be above T_A and T_{NA} (Bard and Fleury, 1978; Côté, Salmela and Papathanasopoulu, 1992). It should also be noted that studies have demonstrated significant improvements in cognition at workloads that are below that normally required to induce T_A and T_{NA} (Brisswalter *et al.*, 1997; Davranche *et al.*, 2005a). Similarly, correlational studies supply somewhat equivocal results. Studies using metabolites of noradrenaline and dopamine as measures of neuroendocrinological activity in the brain have also failed to show unequivocal results (Peyrin *et al.*, 1987; McMorris *et al.*, 2008a). Only two studies (Grego *et al.*, 2004; McMorris *et al.*, 2008b) have been undertaken examining cortisol and/or ACTH concentrations, again with contradictory findings. Neither study showed a significant relationship between cortisol concentrations and cognition. Δ ACTH, when combined with Δ adrenaline, demonstrated a significant correlation with speed of cognition but not accuracy. However, taking everything into account, I believe that there is a prima facie case for an interaction between acute exercise-induced endocrinological changes and cognition. Moreover, the failure to show unequivocal effects may be methodological.

Methodological issues

The possibility that research designs have been inadequate cannot be dismissed. One major problem has been sample size. Sample sizes range from 17 to 6. The nature of the protocols used means that it is difficult for researchers to get participants. Not many people are keen to have blood taken while exercising to maximum. Even where there are sufficient willing participants, the cost of assaying the blood can be prohibitive, resulting in small sample sizes. Small sample sizes increase the chances of Type II errors. These are difficult problems to overcome. Research grants are the obvious answer but difficult to obtain. Laboratories working together is another possibility. In the short term, it would be useful if authors reported effect sizes. Effect sizes provide a measure of differences that are independent of sample size (see Cohen, 1988)

Alternatives to reporting effect sizes are the reporting of confidence intervals (CI) and CI for effect sizes. Normally we measure the 95% CI. This provides a range of values in which we can have 95% confidence that any parameter must lie (see Clark-Carter, 1997). If a CI is large, it would require a large change in values to show a significant difference. However, if CI is small, only a limited difference in values is needed for a significant change. CI are calculated based on means but CI for effect sizes can also be calculated (Schmidt, 1996).

Another factor to be taken into account is the selective bias in choice of subjects. The type of individual who volunteers to take part in such experiments is normally of above average fitness and used to undertaking heavy exercise, therefore effects may not be the same as for the normal population. Even in the studies where unfit individuals have been used the type of person likely to volunteer is unlikely to be totally representative of a normal sedentary population.

Theoretical issues

Most authors have examined adrenaline and noradrenaline with little interest shown in 5-HT or cortisol. That plasma dopamine has received little attention is not surprising. Plasma dopamine concentrations show little change during exercise and it is questionable as to whether assaying methods are sufficiently robust to measure such small changes (Forster, 1999, personal communication). Cortisol and 5-HT, however, are another matter. Indeed, one may not need to measure 5-HT directly but simply measure changes in plasma tryptophan concentrations. The possibility of 5-HT as a mediator between exercise and cognition when exercise duration is long has logical appeal. Long duration, sub-maximal exercise results in increased usage of fat as the main source of energy. This, in turn, results in the unbinding of tryptophan from free fatty acids in the blood. Tryptophan readily crosses the blood–brain barrier and, within the raphe nuclei, combines with 5-hydroxytryptophan to form 5-HT (Chaouloff *et al.*, 1986). As we saw earlier in this chapter, 5-HT plays a major role in arousal. Moderate increases in 5-HT will aid cognition, while large increases will have the effect of inducing over-arousal. Although there is no empirical evidence for this in exercise and cognition studies, there would appear to be no reason why exercise should not affect arousal in the same away as other stressors. In fact, given the effect of unbound tryptophan on 5-HT synthesis, one would expect exercise to more readily induce increased 5-HT brain concentrations than other stressors. Future research needs to examine the interaction between exercise, cognition and plasma concentrations of 5-HT and/or tryptophan.

Another weakness in research is the limited amount of research examining the interaction between cortisol and cognition during exercise. Grego *et al.* (2004) showed no significant correlation between serum cortisol concentrations and cognition, but these authors used actual cortisol concentrations in their correlations rather than Δ values. Baseline cortisol concentrations differ between individuals (even when taking into account diurnal changes), therefore changes in concentrations, as measured by Δ, are better indicators of changes in stress than actual concentrations (this is true for all endocrines). Similarly, as baseline performance of cognitive tasks differs between individuals, it is better to examine correlations between Δ cortisol and Δ cognitive performance. However, McMorris *et al.* (2008b) failed to find any significant correlations between Δ cortisol and Δ cognitive performance. Δ ACTH concentrations when combined with Δ adrenaline concentrations showed a strong regression correlation with Δ reaction time on a flanker task. That Δ ACTH demonstrated a significant relationship but Δ cortisol did not may be due to the different diffusion rates between the two hormones, because we know that cortisol and ACTH interact.

As we have seen, cortisol is the result of HPA activity. However, it also plays the major role in controlling HPA activity and, in particular, the synthesis of CRH and ACTH. Under moderate stress, cortisol feedback into the hypothalamus inhibits the actions of CRH and ACTH, thus controlling arousal. However, when stress becomes too great cortisol feedback is unable to control CRH and ACTH release, with the resultant effect of increased arousal. When this stage is reached the individual could

be described as being over-aroused. As such, both cortisol and ACTH concentrations are indicative of HPA activity and the brain's attempts to control arousal. The data from the McMorris *et al.* (2008b) study do suggest the possibility that HPA activity may have had some effect on cognitive performance. They certainly strongly support the case for further research into the interaction between SAS and HPA activity, and cognitive function during exercise.

Research examining the effect of exercise on the cognitive functioning of fit and unfit participants may be related to changes in cortisol concentrations. Although not unequivocal, there is evidence to suggest that fit and unfit individuals demonstrate different exercise-cognition effects. This may be accounted for by cortisol changes.

Brisswalter *et al.* (1997) showed that fit individuals demonstrated a significant positive effect of exercise while unfit participants showed an inverted-U effect. However, this was not found by Travlos and Marisi (1995). Brisswalter *et al.* claimed that their results were due to fitness per se. Brisswalter *et al.* had all of the participants working at 20%, 40%, 60% and 80% of their own VO_{2MAX}. Although both the fit and unfit individuals were exercising at the same relative intensities, the biochemical changes would differ, particularly at 60 and 80% VO_{2MAX}. Unfit individuals show a significant increase in plasma concentrations of noradrenaline, adrenaline and lactate at a lower intensity than fit individuals (Acosta *et al.*, 2001).

I suggest a different explanation. Given that increases in lactate concentrations are related to perceptions of pain, while increases in noradrenaline and adrenaline are indicative of physiological stress, feedback to the CNS, via the ANS, would be different between the fit and unfit participants at any given exercise intensity. Therefore, one would expect fit and unfit individuals to perceive high intensity exercise differently. The fit athletes would probably not even be unduly concerned about exercising maximally. They know that this is possible and not dangerous. The unfit participants, however, may become anxious when exercising at high intensities. Thus, the differences may be due to perceptions of stress rather than fitness. This does not answer the question as to why Travlos and Marisi (1995) found no significant differences.

The failure to demonstrate unequivocal results in research comparing fit and unfit individuals may be due to the experimental designs. In all of the studies, participants undertook a VO_{2MAX} test prior to the experiment. Thus, even the unfit would have prior experience of exercising maximally. This may alter the perceptions of stress of some of the participants, thus affecting results. With this in mind, we carried out a pilot study in our laboratory. In order to overcome the habituation to heavy exercise effect found in other studies, we had both fit, who had all previously exercised to maximum, and unfit, who had no previous experience of exercising above a very moderate intensity, undertake a predicted VO_{2MAX} test (Åstrand and Rhyming, 1954). In this test participants only work to ~70% VO_{2MAX}. In the actual experiment, we examined choice reaction time at 40 and 80% VO_{2MAX}. The unfit participants demonstrated a deterioration in reaction time at 80% VO_{2MAX}, while the fit showed a linear improvement. I should point out that these results may have been affected by a gender issue. Of the fit participants 90% were male, while 90% of the unfit were female. However, when we applied gender as a covariate there was no change in

results. Moreover, Yagi *et al.* (1999) failed to show a gender effect on the exercise-cognition interaction.

Despite these results, our data do not provide support for the claim that fit and unfit participants would perceive the stress differently. There were no significant differences in rate of perceived exertion, as measured by the Borg Scale (Borg, 1973), or the perception of emotions, as measured by the Feelings Scale (Gauvin and Rejeski, 1993). One should always be wary when using self-report, therefore I believe that a far better measure of the real perceptions would be a measure of Δ plasma cortisol concentrations. Research is needed to examine the interaction between past experience of high intensity exercise, perceptions of stress, plasma cortisol concentrations and cognitive function.

Chronic exercise

The empirical literature provides no support for an interaction between chronic exercise and cognitive function. However, research into animals shows that BDNF brain concentrations are increased during exercise. Given that BDNF plays a major role in neuroprotection, and learning and memory, the possibility for it playing a major effect in the link between exercise and cognitive function in children and the elderly is likely.

2.6 Developing a neuroendocrinological model for an interaction between exercise and cognition

In this section, I outline a possible neuroendocrinological model for an interaction between exercise and cognition. Hopefully, future research can test this model, which only covers the effect of acute exercise. As we saw above, there is little evidence to suggest that the effects of chronic exercise on cognitive functioning can be explained by neuroendocrinological factors, although BDNF remains an exciting possibility.

Immediately before and during exercise, the hypothalamus triggers the synthesis of catecholamines in the SAS. Dopamine and noradrenaline are synthesized in the brain and noradrenaline is released at post-ganglionic sites as exercise intensity increases. When intensity increases beyond a threshold, adrenaline and, to a lesser extent, noradrenaline are released from the adrenal medulla into the blood. These hormones play important roles in the cardiorespiratory system and in metabolism during exercise. Feedback to the brain, in particular the hypothalamus, from the ANS triggers further activity by the SAS and also the release of noradrenaline and dopamine into the noradrenergic and dopaminergic pathways in the brain. These pathways are important in the activation of cognitive and emotional regions of the brain. It is this system that has been hypothesized as being the key factor in providing a neuroendocrinological explanation for an acute exercise-cognition interaction. However, it is somewhat simplistic to isolate this process from other endocrinological processes taking place in the individual.

As well as initiating the action of the SAS, the hypothalamus triggers the synthesis of cortisol via the HPA. During moderate exercise, the action of cortisol helps modulate HPA activity. However, as exercise increases in intensity and/or duration, cortisol is unable to inhibit the synthesis of CRH and ACTH. As a result arousal increases. This will mean greater activation of the limbic system at the expense of the cognitive centres of the brain, in particular the prefrontal cortex.

The third key neuroendocrinological factor in the interaction between exercise and cognition is the synthesis of 5-HT. During exercise tryptophan in the blood becomes unbound from free fatty acids and crosses the blood–brain barrier into the raphe nuclei, where it interacts with 5-hydroxytryptophan to form 5-HT. 5-HT enters the serotonergic pathways, which affects arousal. Moreover, 5-HT has a negative effect on the synthesis of dopamine. This process is heavily dependent on the organism's use of fat as the energy source and is, therefore, most likely to occur during long duration, sub-maximal exercise.

It would appear that when exercise is at an intensity at which brain catecholamines and cortisol concentrations show moderate increases from baseline, cognitive performance can be optimal. In such cases, the noradrenergic and dopaminergic pathways can readily activate the cognitive centres of the brain, while the action of cortisol helps modulate arousal. As exercise intensity increases, however, the controlling effect of cortisol disappears. Moreover, there is an excess of noradrenaline and dopamine, which may well activate the limbic system. In long duration exercise, this can be exacerbated by the activity of the serotonergic system.

While this model has intuitive appeal it should be remembered that brain concentrations of catecholamines and cortisol are not only affected by feedback from the ANS but also by perception and emotions. Thus, for the unfit individual there may be increases in brain concentrations due to perceptions of fear as well as due to exercise. This would result in a decrement in performance at an earlier stage than that for the fit individual, who does not perceive the task as fearful. Thus, the neuroendocrinological explanation is linked to the cognitive psychology and cognitive neuroscience rationales outlined in Chapters 1 and 3, respectively.

Summary

This model suggests an interaction between the SAS and HPA resulting in the synthesis and secretion of catecholamines, 5-HT and cortisol in the brain during exercise. Thus, it is more complex than the catecholamines hypothesis postulated by Cooper (1973), Chmura, Nazar and Kaciuba-Uscilko (1994) and McMorris *et al.* (1999). I believe that future research should set out to examine this model.

In this chapter, I have suggested that catecholamines activity may be best examined by measurement of plasma concentrations of metabolites rather than the actual neurohormones themselves. Perhaps a better way would be to examine ratios between the neurohormones and their metabolites. This would allow the researcher to examine availability *and* usage. This is important, as we assume that increased availability means increased usage.

3

The transient hypofrontality theory and its implications for emotion and cognition

Arne Dietrich

This chapter has two clear goals. First, I will explain the transient hypofrontality theory (THT). The central idea behind the THT is that the brain, in order to drive the bodily motion, is forced to make profound changes to the way it allocates its metabolic resources. This follows – quite simply, actually – from three fundamental principles in neuroscience: (1) the brain has a finite energy supply; (2) physical motion is, computationally speaking, an extremely demanding task; and (3) information processing in the brain is based on competitive interactions among neurons. So, during exercise the brain sustains massive and widespread neural activation that runs motor units, assimilates sensory inputs and coordinates autonomic regulation. This activity must take metabolic resources, given their limited availability, away from neural structures whose functions are not critically needed at the time. According to the THT, these areas are in the prefrontal cortex and, perhaps, the limbic system.

Although based, as mentioned, on well-established concepts in neuroscience, the THT was originally regarded as quite radical. This, I suspect, was due in large part to the fact that it ran counter to several widely accepted but mistaken beliefs about the effects of exercise on brain function and, by extension, mental health. Perhaps the most harmful of these were, actually still are: (1) exercise boosts blood supply to the brain and, therefore, oxygen and glucose uptake; (2) bodily motion is taxing for muscles, no doubt, but it is not something that forces the brain into its computational reserves like, say, playing chess or writing a philosophical treatise; and (3) any improvements in mental health – stress relief, mood elevation, anxiolysis, that sort of thing – must surely emerge from some process that activates, or at least reactivates, a neural region that was hitherto not running on all cylinders. How can decreasing the

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activity of a brain area be good for you? These misbegotten notions, be they factually mistaken or simply the artifacts of misguided theorizing, are so deeply embedded, particularly among psychologists and exercise scientists, that genuine progress in the search for a neural mechanism for the psychological effects of exercise has been virtually nonexistent for decades. I, therefore, see part of my task in this chapter as being to methodically demolish them and disabuse anyone of their residual validity. This, it seems to me, is an essential step. The THT, and its implications for emotion and cognition, cannot be understood without clearing the ground of the fallout of this kind of myopic thinking.

The second goal of this chapter is to flesh out, in some detail, the psychological consequences of the THT. Here, too, it has been my experience that the THT is grossly misunderstood. Again, this is due, for the most part, to misbegotten ideas, only here the trouble is caused not by weak scholarship but by the lack of contact between the rapidly expanding knowledge base of cognitive neuroscience on the one hand and other disciplines interested in the effects of exercise on mental processes on the other. More pointedly, the picture emerging from work on the neural basis of higher cognitive functions is making it clear that the brain's two cognitive information-processing systems, the explicit system, which is primarily enabled by the prefrontal cortex, and the implicit system, have rather different, and in some ways even opposing, functions. This realization has not percolated through to other fields, such as sports psychology, despite the obvious relevance this has to an organism's ability to perform smooth, sensory-motor integration of the kind that characterizes sports and exercise.

According to the THT, an exercising individual enters, sooner or later, a mental state marked by a transient decrease in prefrontal function. Less neural activity in the prefrontal cortex does not mean, though, that a runner or cyclist, after completing a few miles, turns – if you pardon the expression – into a speeding 'dimwit' unencumbered by higher thought processes, an unguided missile, if you will, the likes of which have not been seen since Phineas Gage. Although profound alterations to mental status (hallucinations, for one) are possible for people so physically fit that they can maintain exercise for a very, very long time, thereby causing severe prefrontal hypometabolism (think ultramarathon here); the downregulation is typically much more subtle in most cases and does not lead to any dramatic loss of abilities such as planning a course of action, buffering sub-goals in working memory, maintaining focused attention or any of the other mental wonders bestowed upon us courtesy, mostly, of the prefrontal cortex. What must be understood, first and foremost, is what, exactly, the functions of the prefrontal cortex are, for which tasks they are truly needed, especially in humans, and what effect the inhibition of the explicit system, which is built for mental flexibility, has on the implicit system, whose very purpose is the speedy and efficient execution of sensorimotor tasks.

To clarify some of these matters and prevent further confusion from taking hold, I also provide in this chapter, in addition to some background information on computational issues in motor control and a brief exposition on the functional neuroanatomy of higher mental processes, some examples from the field of sport

psychology of what it means, phenomenologically speaking, to be in a state of hypofrontality. These examples are designed as crutches for the imagination, intuition pumps if you will, to grasp some of the more counterintuitive claims made by the THT.

By the end, I hope to show that an exercise-induced state of frontal hypofunction provides a coherent neuroscientific explanation for the seemingly disparate data in the field of exercise and sport psychology and thus unites, into a single theory, research that currently cannot be satisfactorily accounted for by any other single theory. Moreover, and more importantly, the THT makes, by virtue of providing a sound, mechanistic explanation for the effects of exercise on emotion and cognition, clear and precise predictions that can be subjected to empirical research.

3.1 Clearing the ground

We know, from experimental and anecdotal evidence, that prolonged physical exercise alters mental status. In the moderate aerobic range, in particular, exercise promotes emotional wellbeing by reducing stress, decreasing anxiety and alleviating depression (Salmon, 2001). Although the data, as we will see, are more complex here, exercise also enhances, albeit mildly, cognition and appears to have neuroprotective effects; that is, it delays the cognitive decline associated with aging (Colcombe and Kramer, 2003; Etnier *et al.*, 1997).

Despite decades of research in this field, though, we have no idea why; that is, we do not understand the mechanisms in the brain that mediate the positive effects exercise has on mood and cognition. Since the mid-1970s, for more than 30 years now, scientists have been stuck in a rut when it comes to explaining how, exactly, putting one foot in front of the other – at a certain speed, for a certain amount of time – makes you have creative insights or feel 'peachy'. If this question is put to laymen, two theories are typically offered – in a knee-jerk fashion, almost – to explain this phenomenon. One claims that exercise increases blood flow to the brain (the more-blood theory or MBT) and the second points the finger at the endorphins. Despite popular belief to the contrary, this, however, does not explain it. While the MBT is wrong outright, the endorphin hypothesis rests on very sketchy evidence – the best of which was published only very recently (Boecker *et al.*, 2008) – which cannot, at any rate, account for the psychological data. But without an alternative theory on the horizon, scientists neither pursued the matter further nor bothered to rectify publicly these misbegotten ideas. This has led to the curious situation that the problem, despite constituting a rather embarrassing gap in the medical knowledge base, continues to loom large, while, at the same time, the general public believes it to be more or less resolved.

This situation has changed and there is much renewed interest in the field. Broadly speaking, the attack on the problem is led on three fronts. One focuses on molecular and cellular changes, such as neurotrophic factors – brain-derived neurotrophic factor (BDNF) and nerve growth factor (NGF), mostly – or neurogenesis (for a recent

review, see Cotman and Berchtold, 2007). The second focuses on neurochemical changes (for recent reviews, see Dietrich and McDaniel, 2004; Dishman *et al.*, 2006). This approach is not new actually, but has nevertheless experienced a resurgence of late. There has always been a tendency, perhaps due to the stunning success of psychopharmacology in treating anxiety disorders and depression, to concentrate heavily on alterations in neurotransmitter systems to explain the mood-enhancing effects of exercise and, indeed, much work has been done on dopamine, noradrenaline, serotonin (5-hydroxytryptamine), and, most recently, endocannabinoids. However, we also know, certainly since the advent of neuroimaging technology, that mental disorders such as the mood disorders are also characterized by neuroanatomical abnormalities. This suggests, at the very least, that neurochemical mechanisms alone can only provide part of the answer, a fact that has long been realized in the neurosciences.

In any event, both approaches, the molecular and the neurochemical, are better at accounting for the long-term effects of exercise on mental health. But what about immediate or short-term effects? How is it possible to run for, say, 30 minutes, and feel instantly better about yourself? Drugs such as Prozac certainly do not work that way – although this analogy is not offered here as a rigorous pharmacological counterargument. Or how, exactly, does cycling speed up reaction time in simple decision-making tasks, which it does (Davranche *et al.*, 2005), without sacrificing – within limits, of course – accuracy? Neurogenesis, despite its appeal in recent years, helps us little here. To account for the effects of an acute bout of exercise on psychological function, we need a quicker mechanism, one that relies on rapid changes in the activity of neuronal populations. This, then, is the third approach, and the one taken by the transient hypfrontality theory. At the core of the THT is a physiological mechanism that is based on local, need-based shifts in the global cerebral metabolism, a concept so firmly established in cognitive neuroscience that it serves as the rationale for all neuroimaging research. The psychological consequences of these exercise-induced shifts in metabolic resources then simply follow from what we know about the neuroanatomical basis of emotion and cognition.

Before we get to the 'nuts and bolts' of the THT, though, we need to take time out and disabuse anyone of the residual validity of the claim that changes to mental processes are due to increased blood flow to the brain. This must be done, I am afraid, because this notion is not a benign crutch for the imagination but pernicious fallacy of thinking that as long as we keep it, lures us into taking paths that lead nowhere good. Whenever this seductive danger presents itself, it might help to remind yourself that given what we know about the brain, this idea must be wrong. As cognitive neuroscience is making serious contact with exercise science, we must, from the outset, clear the ground of this misbegotten fossil trace from a bygone era.

Let us examine then the MBT and, while at it, its two close cousins, the more-glucose theory (MGT) and the more-oxygen theory (MOT). How, exactly, is more blood supposed to reduce anxiety or depression, as, let us not forget, we are concerned with a *neural* mechanism here. If a friendly neurologist, for instance, were to find a way to pump some more blood into your brain, do you think it would

make you feel better? During light to moderate exercise, *global* blood flow to the brain, along with global cerebral metabolism and uptake of oxygen, remains constant (Ide and Secher, 2000; Sokoloff, 1992). To repeat, despite several physiological parameters changing – total cardiac output, blood velocity, blood pressure, and so on – and large, *regional* shifts in blood perfusion occurring within the brain, the global value, as determined by the Kety-Schmidt technique, does not change during exercise. Indeed, during strenous exercise, global cerebral perfusion, if anything, *de*creases (Nybo and Secher, 2004). The brain is the only organ of the body that does not receive blood according to need, as, for instance, the stomach or muscles, but enjoys a rather steady perfusion rate, regardless of what a person does (editors' note: see Chapter 10 for a different interpretation).

To understand the hemodynamic interplay a little, consider, for instance, cardiac output. At rest, the average male has a cardiac output of about $5.8\,l\,min^{-1}$. This amount is divided up among all bodily tissues with the brain receiving a share of about 15% or 750 ml. At light exercise, total cardiac output increases – the heart beats faster now – to about $9.4\,l\,min^{-1}$, but this increase is pumped, for obvious reasons, to the skeletal muscles. What is more, the 'greedy' muscles require all they can get and the percentage of cardiac output that flows to the brain is actually reduced to 8% of the total, which, however, is not a problem for the simple reason that the total cardiac output is now also higher. In fact, this 8% comes out, as it happens, to a volume of $750\,ml\,min^{-1}$. During heavy exercise, the brain receives only 4% of cardiac output but, given the overall output, at this intensity, of $17.5\,l\,min^{-1}$, this reduction is precisely offset to yield a perfusion rate of, again, $750\,ml\,min^{-1}$ (see, for instance, Åstrand and Rodahl, 1986). So the brain, as result of this interaction, has a constant and steady supply of blood, despite other cardiovascular parameters changing. In sum, contrary to popular conception, there is no evidence to suggest that the brain is the recipient of additional resources of any kind during exercise (Dietrich, 2003).

3.2 Exercise-induced transient hypofrontality

Once we are clear about this, we can consider alternatives. The central idea behind the THT is that the brain, in order to drive the bodily motion, is forced to make profound changes to the way it allocates its metabolic resources. This follows from the facts that: (1) the brain has a finite energy supply; (2) that bodily motion is an extremely demanding task in *computational* terms – that is for the brain, not the body; and (3) that neural processing occurs on a competitive basis. A cornerstone of cognitive science holds that humans have a limited information processing capacity at the bottleneck of consciousness. But there also exists a cap on the total amount of information processing – unconscious and parallel, that is – that can occur at any one time. In other words, the brain cannot maintain activation in all its networks at once and activity in one structure must come at the expense of others. In the case of exercise, the enormous demands on motor, sensory and autonomic structures result

in fewer resources available for computations in those neural regions not involved in maintaining the motion.

At this point, it is perhaps useful to interject that the THT is a theory with implications beyond physical exercise. It proposes, actually, a common neural mechanism for all alterations to consciousness and holds that whenever the brain is taxed – be it in hyperthermia, hypothermia, hypoxia (i.e. in altitude), exercise, or, for that matter, any condition compromising brain integrity – it starts shutting off brain areas from the top down. Recall that neuroscience conceptualizes cognitive function as hierarchically ordered. Evolutionary pressures forced the development of ever more integrative neural structures able to process increasingly complex information. This, in turn, led to increased behavioural flexibility and adaptability. The cerebral cortex, and the prefrontal cortex especially, sits at the top of this hierarchy, representing the neural basis of higher cognitive functions (Frith and Dolan, 1996; Fuster, 2002).

The THT, then, simply proposes the following. When the brain is under strain, it starts to reserve its limited metabolic resources for operations that are critically needed at the time, which results in the downregulation of neural structures whose computations are not critical for the task at hand. As the strain continues, the brain is forced to go ever deeper into safe mode and the THT simply suggests that this decline progresses from brain areas supporting the highest cognitive functions, down the functional hierarchy, one phenomenological subtraction at a time, to brain areas supporting the most basic ones. So the prefrontal cortex, being the most zenithal higher-order structure, is the first region whose computations are no longer supported sufficiently to reach muscles or consciousness. Prolonged physical exercise is simply one example of a general neural mechanism that accounts for the phenomenology of all altered states of consciousness, as, indeed, the experience of timelessness, living in the here and now, reduced awareness of one's surroundings, and diminished analytical or attentional capacities – all subtle modifications of mental functions that are typically ascribed to the prefrontal cortex – is consistent with a state of frontal hypofunction (Dietrich, 2003). In most conditions or techniques producing alterations to mental function, prefrontal hypoactivity is all that is necessary, hence the name of the theory. However, if the strain continues, and, to stay with exercise, the person keeps on running, say, the 135 miles Badwater Marathon, they are, sooner or later, reduced – in an onion-peeling principle of sorts – to their most basic mental capabilities.

Although evidence for a transient downward shift in activity in prefrontal regions during exercise has been described for the past few decades in animals and humans, using a variety of different methods and paradigms, the idea that the psychological effects of exercise might be due to cortical *de*activation, especially in prefrontal regions, was so completely against the accepted wisdom of the time that no one 'connected the dots'. Even when I formulated the THT in 2003 (Dietrich, 2003, 2004a), the theory had little impact in exercise psychology. This, I believe, is due to three reasons. First, the misconception, widely held even among scientists who concern themselves with exercise, to say nothing of the general public, that exercise

increases blood flow to the brain prevents one from understanding the pivotal resource limitation the brain must solve. As long as individuals hold on to some version of the infinite-mind idea, be it in the form of an unlimited energy supply or the 'we-only-use-10-percent-of-the-brain' notion, one cannot conceive of the THT. The fact that the brain shifts its resources locally is powerfully demonstrated with every neuroimaging study.

Second, motion was not understood, certainly not in cognitive psychology, as a biocomputation of the highest order. Without this realization, however, it is impossible to grasp the implications of exercise, especially those involving large muscle groups, on the brain's limited resources and thus its ability to process other, cognitive or emotional, information at the same time. There is a long-standing belief in cognitive psychology that automatic behaviours do not require mental resources, whereas effortful ones do. This, however, cannot be. Consider, for instance, artificial intelligence, a field in which motion is readily recognized as a huge *computational* problem. Human artificers have managed to create machines that beat you in chess in eight-and-a-half moves with half of their transistors unplugged; yet, they cannot make a robot that walks on two feet, let alone one that makes a decent tennis serve. It certainly is not because they cannot make the moveable equipment – arms, legs, joints, and so on. The reason is that sensorimotor integration, in real time, requires an astronomical amount of number-crunching. During simple walking, the brain must control millions upon millions of muscle fibers to precise specification, with every twitch affecting the strength of the contraction of the next. Programming this into a robot has yet to be done successfully. I sometimes wonder how long it will take before the first two-legged robot is the number one tennis player in the world.

Next, consider, the brain's motor system. By simply listing the number of structures devoted to movement you can get an appreciation of the complexity of moving the body around: primary motor cortex; secondary motor cortices (i.e. premotor and supplementary motor area [SMA]); basal ganglia; the motor thalamus; cerebellum; Red Nucleus; substantia nigra; the massive pathway systems; and the motor neurons all along the spinal cord, among rather many others. This represents not just an enormous amount of brain volume but also a very high number, in percentage terms, of neurons. Why, for instance, does the cerebellum have more neurons than any other structure in the brain, including *the entire cerebral cortex*!? What do you think do all these neurons do? And then, let's not forget, movement occurs through space so any motor activity must integrate sensory processes and soon we are at yet another, nearly equally long list of brain structures that must be activated in order to process the relevant perceptual information during exercise. But we have not yet finished because there are also those nuclei mediating autonomic regulation such as, for instance, in the hypothalamus, the reticular formation, and many nuclei in the medulla. At this point, all the person is doing with all this massive brain activation, we remind you, is simply running, nothing else!

Let us examine an even more sensitive point. The male human brain is about 150 g heavier than the female one. It is universally understood that this is due to the male's higher body mass. But consider what this really means. The male brain has, on

average, 8–10% more brain mass only so that he can throw around what amounts to no more than a few more kilograms of body mass. It is hard to believe that moving around a few more kilograms of muscle and bone requires so much more brain mass, especially in percentage terms, given that we are animals who are already copiously equipped neuronally. However, it does. Finally, also keep in mind that the human motor system is more highly evolved than that of other animals. Animals with much smaller brains can produce very complex movements, movements we find extraordinary, but what they cannot do is learn motor acts for which they are counter-prepared, let alone to such a state of perfection the way humans can. Just think of our ability to swim butterfly, pole vault, or play the violin, all actions we are not designed to perform. Try teaching these to the next chimpanzee.

These arguments are not, of course, sound evidence as far as neuroscience goes; I simply offer them here to help you start thinking of motion in terms of its neural costs. Psychologists and exercise scientists would do well to understand exercise as a computational issue that requires vast amounts of resources *for the brain*. With this in mind, let us review some of the evidence supporting this view.

Several techniques such as ^{133}Xe washout, radioactive microsphere and autoradiography, as well as electroencephalography (EEG), simple-photon emission computed tomography (SPECT) and positron emission tomography (PET), have been used to measure brain activity during exercise. Converging evidence from these studies indicates that exercise is associated with profound regional changes in motor, sensory and autonomic regions of the brain. Marked increases in activation occur in neural structures responsible for generating the motor patterns that sustain the physical activity. In particular, the primary motor cortex, secondary motor cortices, basal ganglia, cerebellum, various midbrain and brainstem nuclei, motor pathways, as well as several thalamic nuclei are involved. In addition, exercise activates structures involved in sensory, autonomic and memory function, particularly primary and secondary sensory cortices, sensory pathways, brainstem nuclei, hypothalamus and the sensory thalamus. Cerebral blood flow (CBF) and local cerebral glucose utilization (LCGU), both indices of the functional activity of neurons, have confirmed this pattern of neural activity in exercising animals (Gross, Marcus and Heistad, 1980; Holschneider *et al.*, 2003; Sokoloff, 1991; Vissing, Anderson and Diemer, 1996).

In the most comprehensive study to date, Vissing, Anderson and Diemer, (1996, p. 731) concluded that 'marked exercise-induced increases in LCGU were found in cerebral gray matter structures involved in motor, sensory and autonomic function as well as in white matter structures in the cerebellum and corpus callosum'. In their study, rats ran for 30 minutes on a treadmill at 85% of maximum volume of oxygen uptake, and they found highly significant increases in LCGU in all brain structures *except* in the prefrontal cortex, frontal cortex, cingulum, CA3, medial nucleus of the amygdala, lateral septal area, nucleus accumbens, a few hypothalamic nuclei, median raphe nucleus, interpeduncular nucleus, nucleus of the solitary tract and inferior olive. Taken together, these neural regions represent but a small percentage of total brain mass confirming that physical exercise requires massive neural activation in a

large number of neural structures across the entire brain. It follows that prolonged aerobic exercise would require the *sustained* activation of this large amount of neural tissue.

Physiological data on human brain activity during exercise is remarkably sparse but consolidate, not surprisingly, the data in the animal literature. The various methods used to map neural activation patterns in animals cannot be used in humans for obvious ethical reasons and most neuroimaging techniques are also not viable options because they preclude head movement. In addition, it is also not possible to scan subjects – with functional magnetic resonance imaging (fMRI), for instance – immediately following exercise. Neuroimaging studies show that the pattern of neural activation associated with a particular task rapidly returns to baseline levels after the cessation of that task. Indeed, this is the very theoretical basis of interpreting neuroimaging studies; the temporal association of task performance to brain activation. This suggests that a delay of even a *few seconds* would be sufficient to start normalizing any exercise-induced regional changes in neural activity.

There are ways around this, through, and in one PET study, increased brain activation was recorded in the 'primary sensory cortex, primary motor cortex, supplementary motor cortex as well as the anterior part of the cerebellum' in response to cycling (Christensen *et al.*, 2000 p. 66), while a single photon emission computed tomography (SPECT) study found increases in regional cerebral blood flow (rCBF) in the supplementary motor area, medial primary sensorimotor area, the striatum, visual cortex, and the cerebellar vermis during walking (Fukuyama *et al.*, 1997). These and other studies are still limited, as evidenced by a comparison with the brain activation seen in rCBF studies in animals, because they are based on keeping the head as still as possible. However, this requires the whole body to move as little as possible. As we will see later, this is a fatal confound. The resource issue of motion depends on the amount of muscle mass moved, as well as the intensity and duration it is moved, with whole-bodily motion at a strenuous intensity being an entirely different matter than cycling, in supine position, for a few minutes at an intensity so low that subjects manage to keep their heads still enough to produce artifact-free images in the brain scanner. For the same reason, brain activation measured by neuroimaging studies using mental imagery as a substitute for real motion bears little resemblance to the brain activation present in individuals that are actually in full motion. We shall return to this topic later.

Another way around this entire problem is the 18-fluorodeoxyglucose (18FDG) PET technique. 18FDG allows for functional mapping of brain areas *during* motion because the glucose uptake occurs actually during the movement. Because this compound is not readily metabolized by neurons, it stays fixed long enough for the scanner to detect the regional changes of glucose uptake later. In other words, the main disadvantage of PET, compared to fMRI – its poor temporal resolution – can be used to our advantage here. This allows one to produce a functional index of the moving human brain. So far, two studies have done this (Kemppainen *et al.*, 2005; Tashiro *et al.*, 2001). Both confirmed the massive brain activation that occurs as a function of large-scale bodily movement. Importantly, they found, as predicted by

the THT, general cortical deactivation and, specifically, highlighted the deactivation in prefrontal regions (Tashiro *et al.*, 2001) and the link of this prefrontal hypometabolism to fatigue (Kemppainen *et al.*, 2005). This is direct confirmation of the THT. In both cases, subjects ran for a mere 10 and 5 minutes, respectively. We are currently conducting an 18FDG study in our laboratory to map the brain activation after longer bouts of treadmill running.

With this in mind, let us consider other lines of evidence in support of the THT, some of which are, as already mentioned, decades old. EEG studies, for instance, have consistently demonstrated that exercise is associated with alpha and theta enhancement, particularly in the frontal cortex (Boutcher and Landers, 1988; Kamp and Troost, 1978; Kubitz and Pothakos, 1997; Nybo and Nielsen, 2001a; Petruzzello and Landers, 1994; Pineda and Adkisson, 1961; Youngstedt *et al.*, 1993). An increase in alpha activity is a putative indicator of decreased brain activation (Kubitz and Pothakos 1997; Petruzzello and Landers, 1994). For instance, Kubitz and Pothakos (1997, p. 299) concluded that 'exercise reliably increases EEG alpha activity', while Petruzzello and Landers (1994, p. 1033) stated that 'there was a significant decrease in right frontal activation during the post-exercise period'. Additional evidence for the theory comes from a human study that correlated the rating of perceived exertion (RPE) with EEG activity (Nybo and Nielsen, 2001a). Recording from three placements (frontal, central and occipital cortex) during sub-maximal exercise, Nybo and Nielsen found that 'altered EEG activity was observed in all electrode positions, and stepwise forward-regression analysis identified core temperature and a frequency index of the EEG over the frontal cortex as best indicators of RPE' (p. 2017). This finding suggests that exercise is not only associated with decreases in frontal activity but also that the degree of physical effort might be correlated with the severity of frontal deactivation. When reading these, in part, 30 year-old articles, one is struck by the extent to which the authors struggled to explain their electrophysiological results. Not a single one concluded, presumably because of what they falsely thought this meant for mental health, that exercise deactivates neocortical regions or, worse, the prefrontal cortex, our most sophisticated brain area. It just did not make sense to them, though the evidence was right there.

Single cell recording in exercising cats has also provided support for decreased activation in prefrontal regions. Recordings from 63 neurons in the prefrontal cortex, units associated with the control of the movement showed increased activity during locomotion, while other prefrontal units decreased their discharge (Criado *et al.*, 1997). Finally, the studies on CBF and metabolism (e.g. Vissing, Anderson and Diemer, 1996) reviewed above have provided strong support for the hypothesis that exercise decreases neural activity in the prefrontal cortex. As cited above, Vissing, Anderson and Diemer (1996) found highly significant increases in LCGU in all but a few brain structures. In sum, *this pattern of activity is so striking that extended aerobic running should be regarded as a state of generalized brain activation with the specific exclusion of the executive system.*

The evidence in support of the THT is, at this point, convergent and convincing, without any data contradicting it. Thus, sensory-motor integration tasks involving

large-scale bodily movement, such as physical exercise, require massive and sustained neural activation of sensory, motor and autonomic systems. Given the fact that the brain operates on a fixed amount of metabolic resources, exercise must place a severe strain on the brain's limited information processing capacity. This should result in a concomitant transient decrease in neural activity in structures that are not directly essential to the maintenance of the exercise. Such need-based shifts of resources have been observed at a smaller scale in response to treadmill walking. Using a rat model, Holschneider *et al.* (2003, p. 929) reported that the 'significant decreases in CBF-TR noted in primary somatosensory cortex mapping the barrel field, jaw and oral region suggests a redistribution of perfusion away from these areas during the treadmill task'. Naturally, such costs and benefits associated with efficient information processing are a direct consequence of the principles of evolution (Edelman, 1993; Pinker, 1999). Indeed, the hypothesis is consistent with the fundamental principle that information processing in the brain is competitive (Dietrich, 2007; Miller and Cohen, 2001). Thus, in addition to competing for access to consciousness (Crick and Koch, 1998), brain structures are subjected to an overall information-processing limit due to finite metabolic resources. Put another way, the brain downregulates neural structures performing functions that an exercising individual can afford to disengage. Depending on the type of exercise, the THT proposes that these areas are, first and foremost, the higher cognitive centres of the frontal lobe, and, to a lesser extent, emotional structures such as the amygdala (Dietrich, 2004a, 2006).

The third reason why the THT did not receive, initially at least, a warm reception in circles outside neuroscience is that benefits to mental health – improvement to mood and cognition – could not be conceived of as resulting from cortical deactivation. In the prevailing zeitgeist prior to the wonders of neuroimaging, it did not make any sense that one could, during exercise, think more clearly, have creative ideas and feel uplifted and ecstatic because one *inhibits* the pinnacle of human evolution, the prefrontal cortex. Let us call this the 'activation-is-good' fallacy. It is actually a symptom of a more general malaise in fields outside cognitive neuroscience where a gross misunderstanding or simplification of what, exactly, the prefrontal cortex does and does not do often prevails. This brings us to our next point.

3.3 Implications for emotion

In this section, we examine the result of exercising on emotion and cognition. We start, briefly, with emotion and move onto cognition. Prior to the THT, there was no unifying framework for the psychological consequences of acute exercise bouts. It is here, though, that the explanatory power of the THT comes into full view, as it accounts, in a single stroke, for a large portion of what otherwise seems to be bewilderingly conflicting data.

Neuroimaging studies of individuals with anxiety disorders and depression show evidence of frontal lobe dysfunction. In obsessive compulsive disorder (OCD) for instance, the ventromedial prefrontal cortex (VMPFC), which has been implicated in

complex emotions, exhibits widespread *hyper*metabolism (Baxter, 1990; Baxter *et al.*, 1987), while individuals with other anxiety disorders, such as post traumatic stress disorder or phobia, show *hyper*activity in the amygdala (LeDoux, 1996). Given the analytical, emotional and attentional capacities of the prefrontal cortex, the excessive activity is thought to generate a state of hypervigilance and hyperawareness leading to anxiety. PET studies reveal a similar picture for depression, which is also marked by *hyper*activity in the VMPFC and the amygdala (Mayberg, 1997; Mayberg *et al.*, 1995). Conversely, the dorsolateral prefrontal cortex (DLPFC), which is associated with higher cognitive functions, shows less than normal activity in depression, depriving the individual of the higher cognitive abilities that might help mitigate the negative mood. Treatment with selective serotonin reuptake inhibitors (SSRIs) results in a normalization of the malfunctioning of this complex prefrontal circuitry (Mayberg *et al.*, 1995), pointing to an abnormal interaction between the VMPFC and the DLPFC rather than global prefrontal dysfunction (Starkstein and Robinson, 1999). Interestingly, healthy subjects asked to think sad thoughts show a similar pattern of activity (Damasio *et al.*, 2000). Considering the similarities in brain activation, it is not surprising that OCD patients frequently develop comorbid major depression and that the treatment of choice for both disorders is SSRIs (Starkstein and Robinson, 1999).

Before neuroimaging – prior to the mid-1990s, more accurately – it was simply not known that affective states, such as depression and several of the anxiety disorders, are accompanied by *excessive* activity in prefrontal regions. Neurobiologists and, by extension, exercise scientists almost exclusively tried to understand the neurobiology of these disorders with neurochemical theories, in no small measure, no doubt, due to the success of neuropharmacology in treating them. But even then it took a long time in neuroscience to demolish the 'activation-is-good' fallacy.

With the concept of exercise-induced transient hypofrontality, a novel neural mechanism by which exercise might be beneficial to mental health becomes immediately apparent. To spell it out, the THT proposes that exercise exerts some of its anxiolytic and antidepressant effects by inhibiting the excessive neural activity in VMPFC regions, and thus reducing the relative imbalance between VMPFC and DLPFC activity. In other words, the massive neural activity due to exercise involving large-scale bodily motion, coupled with the brain's finite metabolic resources, makes it impossible for the brain to sustain excessive neural activity in structures, such as the prefrontal cortex and the amygdala, that are not needed at that time. As the brain must shunt resources away from the very structures that compute the information engendering stress, anxiety and negative thinking, these computations are subtracted from our phenomenology. Put another way, the brain must balance a tight budget and simply cannot afford, whilst performing another very costly task, excessive spending on luxury items. This mechanism ought to work better for the more common, everyday stresses in one's life, which are the result of much milder prefrontal hyperactivity compared to the more pathological hyperactivity associated with disorders, given that most forms of exercise also produce only a mild strain on the brain's metabolic resources. In conclusion, the THT is a contributing causal

mechanism to the psychological changes we see in exercising individuals and it is the only such theory that incorporates recent advances in the neurobiology of depression and anxiety disorders.

Moreover, the THT is currently the only theory that adequately explains why high-intensity anaerobic exercise, such as weight-lifting or sprinting, does not have mood-enhancing effects, a fact that remains difficult to explain for theories solely based on neurotransmitter regulation. Thus, in addition to providing a coherent psychological explanation of the existing data, the THT can also specify the exercise parameters most conducive to mental health promotion, such as intensity and duration.

In sensory as well as motor systems, the brain codes intensity by the rate of neuronal firing. Obviously, an increased rate of discharge increases a neuron's metabolic needs. This is not a minor matter, as the sodium-potassium pump, for instance, which reverses the ion exchange that occurs during an action potential, takes up approximately 40% of the total metabolic resources of a neuron. Consequently, exercising at low intensities, which requires lower firing rates, is less likely to cause metabolic needs in motor and sensory areas that require the brain to shift its limited resources away from areas unrelated to the task. This notion is supported by the finding that contrary to moderate and heavy exercise, light dynamic exercise in humans does not increase cortical blood flow (Globus *et al.*, 1983). Conversely, exercise of high intensity, which is supported by very high firing rates, introduces a second limiting factor, the cardiovascular system. Intense exercise, then, is simply impossible to maintain long enough in order to tax the brain's resources. A moderate physical workload, on the other hand, would be associated with a considerable increase in neuronal firing rates in a large amount of neural tissue that can be sustained, by the cardiovascular system, for a long period of time. This should lead, in turn, to more profound hypofrontality. The THT predicts, then, that exercise intensity at the anaerobic threshold, which might be a walking pace for one person and a 6-minute mile for another, is the effort most conducive to force a reallocation of resources at the expense of higher cognitive and emotional structures. This fits well with clinical data showing that exercise in the moderate, aerobic range is most beneficial to mental health (Salmon, 2001; Scully *et al.*, 1998). Thus, in contrast to neurochemically based theories, transient hypofrontality accounts for factors known to most strongly correlate with the efficacy of exercise as a treatment for anxiety disorders and depression.

3.4 Implications for cognition

The implications for cognitive functions are more multifaceted. This arises from the fact that the brain runs two anatomically and functionally separate information-processing systems and a state of transient hypofrontality affects each system in different, at times even opposing ways. Understanding the specifics requires a brief but entirely necessary detour into cognitive psychology. The main points for

discussion are, first, explicit tasks that are strongly associated with prefrontal function, such as those tapping heavily into working memory, sustained and directed attention, and complex social emotions, are impaired during exercise (Dietrich and Sparling, 2004). The heavier the strain the brain is under, that is, the more strenuous the exercise – muscle mass involved, duration, intensity, and so on – the more severe the impairment. At no point during exercise are prefrontal-dependent processes enhanced. This, however, does not preclude the possibility – or the fact, actually, given the evidence – that those processes are enhanced post-exercise or, for that matter, decline at a slower rate during aging in people with a life-long habit of exercising (Colcombe and Kramer, 2003). The neural mechanisms for these latter effects are likely to be different in kind.

Second, implicit tasks, which are those that are characterized by simple or automated stimulus-response affairs (reaction-time tasks, visual discrimination tasks with few choices, etc.), can be both enhanced and impaired, depending on the type of exercise. According to the THT, the downregulation of the explicit system in the prefrontal cortex during exercise, especially at the beginning of exercise, disinhibits the implicit system. Because the quality of the execution of an implicit task is optimized when the neural control is entirely in the implicit system, speed and accuracy on such tasks are initially enhanced. This is further strengthened by the activation of the arousal system in the brainstem. In other words, the enhancement seen on implicit tasks during and immediately following exercise is likely a factor of both transient hypofrontality and neurotransmitter modulation. However, if an athlete's cardiovascular system is trained enough to continue the exercise, the brain is increasingly forced to divert metabolic resources to the motor system and, eventually, has no choice but to tap into the resources of the implicit system as well, ultimately compromising its ability to process information. Near exhaustion, as shown clearly by the data (e.g. Cian *et al.*, 2000), there is, just as predicted by the THT, impairment on cognitive function of all kinds, including implicit ones. Note that such deficits on implicit tasks are difficult to explain in terms of a neurochemical-mediated arousal mechanism alone, as there is certainly enough arousal going on at the end of a marathon. In any event, distinguishing between explicit and implicit processing is imperative when trying to understand the effects of exercise on cognitive function.

Computational issues in skilled motor performance

The brain operates two distinct information-processing systems to acquire, represent and implement knowledge. The explicit system is rule-based, its content can be expressed by verbal communication and it is tied to conscious awareness. In contrast, the implicit system is skill or experience-based. Its content is not verbalizable, can only be conveyed through task performance and is inaccessible to conscious awareness (Ashby and Casale, 2002; Dienes and Perner, 1999; Schacter and Bruckner, 1998).

Recent advances in cognitive neuroscience have begun to identify the brain circuits underlying the explicit system. Evidence that the working memory buffer of the

DLPFC holds the current content of consciousness, coupled with evidence that the executive attentional network of the DLPFC is the mechanism to select the content (Baddeley, 1996b; Cowan, 1995), suggests that the explicit system is critically dependent on prefrontal regions (Ashby and Casale, 2002; Dehaene and Naccache, 2001). Abundant evidence also suggests that medial temporal lobe structures are involved (Poldrack and Packard, 2003). The neural substrates of the implicit system are less clear. The basal ganglia have been implicated most often, and they are critical for a type of implicit memory known as procedural memory (motor and cognitive skills), but contribute to other types as well, such as priming, conditioning and habituation (Mishkin, Malamut and Bachevalier, 1984; Poldrack and Packard, 2003). Research on animals, brain-damaged patients and neuroimaging studies of healthy subjects have shown that these systems can be dissociated from each other functionally and anatomically (Schacter and Bruckner, 1998; Squire, 1992).

From an evolutionary perspective, the existence of two distinct systems for knowledge representation indicates that each must be specialized in some way. To illustrate this using an example by Crick and Koch (1998), a frog responds stereotypically, zombie-like if you will, to visual input, that is to small, prey-like objects by snapping and to large, looming objects by jumping. These responses are controlled by rigid and reflexive but fast-responding and efficient systems. As the number of such reflexive systems must grow to handle increased complexity, such an organization becomes uneconomical. A more advantageous solution is to evolve a single system capable of temporarily buffering and sustaining multiple representations, so that the organism can examine them before making an output decision. This is particularly useful when two or more of the organism's systems generate conflicting plans of action. Thus, implicit knowledge can be thought of as task-specific and has the advantage of being more efficient, while explicit knowledge has evolved to increase behavioural flexibility (Dietrich, 2004a).

This flexibility/efficiency trade-off between explicit and implicit control of skilled movement is best described in computational terms. The mechanism(s) by which knowledge shifts from an unconscious (implicit) state to a conscious (explicit) state is one of the most fundamental questions of cognitive science and consciousness (Cleeremans and Jiménez, 2002). From a theoretical point of view, this boundary is not sharp and several steps might occur before knowledge is fully accessible to consciousness (Karmiloff-Smith, 1992). Dienes and Perner (1999) provide the following example: 'I know that this is a cat'. This information has three elements: (1) the content (this is a cat); (2) the attitude (knowing, as opposed to a different attitude, for instance, wishing); and (3) the holder (I – rather than you). At the lowest level, the content (this is a cat) is part of the information-processing system and can be put to use, that is run away if the system is a mouse brain. This is the level of procedural knowledge and it leaves the elements of attitude and holder implicit. At the next level, the system represents the attitude explicitly, that is, the system *predicates* the information to be knowledge (rather than a wish). The system now not only possesses and uses the information but also represents what it is that it possesses and uses. In other words, it labels it as knowledge. This is a higher-order or

meta-representation that makes the information useable for other parts of the system. This, however, leaves implicit whether or not the information is a fact. Information can be false, and the ability to engage in hypothesis testing necessitates that we can distinguish between true and false, which requires the validity of the information be made explicit in a higher-order representation. Thus, at the next level, the system represents content, predication and 'factivity' but leaves implicit the holder. Only if the holder also becomes a higher-order representation can we speak of information as fully explicit or fully conscious (Kihlstrom, 1996). Also, it is only then that we can verbally communicate the knowledge.

This makes clear why procedural knowledge is so limited in its usability. Because it is impossible for the implicit system to determine whether or not something is a fact (implicit knowledge treats all events as true), it cannot represent the knowledge as a hypothetical possibility, making it inflexible and idiosyncratic (Dienes and Perner, 1999). This also explains why procedural knowledge, such as motor skills, is more efficient. Higher-order representations exponentially increase computational complexity. Given the already high complexity of even the simplest of motor skills, a fact that is readily recognized by the artificial intelligence community, the explication of motor knowledge would become a serious resource issue. Indeed, full explication of a motor skill is impossible because information in the explicit system is subject to the limits of working memory capacity (Cowan, 2001) and the number of dimensions we can explicitly manipulate in parallel is thought to be one quarternary relation (Halford, Wilson and Phillips, 1998). But a motor task such as a tennis serve involves more than tossing the ball straight in the air, swinging the racket in an arc, hitting the ball as it descends and following the motion through. Consider, for instance, what it would take to write a computer programme that specifies each muscle twitch in the correct order and intensity to produce a world-class tennis serve. The amount of information that must be held concurrently in the focus of attention far surpasses the computational limit of working memory. In contrast, procedural knowledge is contained in the application of the procedure and need not be extracted from general rules that are represented at a higher-order level and then applied to a specific example. Motor skills are more efficient because they leave implicit predication, 'factivity' and the reference to self.

This efficiency of procedural knowledge is paramount to motor skills because purposeful movement must occur in real-time. As an example, consider the lightening-fast escape manoeuvres of a squirrel. Lacking an overall strategy or plan, the squirrel gets to safety entirely by relying on moment to moment adjustments. Such smooth feedback-driven sensory-motor integration can produce extremely complex movement patterns that can serve an overall and/or higher goal (safety), yet requires no more than the reaction to immediately preceding input. This is not unlike an outfielder trying to catch a flyball. Starting with only a vague idea as to the ball's ultimate location, the player progressively approximates that location by continuously adjusting his movements based on updates of the ball's trajectory and speed as it approaches (McLeod *et al.*, 2001). Because these are fluid situations occurring in real time, they require, first and foremost, efficiency. A system is most efficient if it

represents knowledge in a fully implicit manner; that is, it codes the application of the knowledge within the procedure and refrains from buffering any other property – predication, 'factivity', time – of the information in a higher-order representation. On the flip side, this set-up is the reason why motor behaviour must progress stepwise from immediately preceding input. The lack of meta-representation precludes the system from calculating hypothetical future scenarios that would enable it to anticipate several steps in advance.

Framed in computational terms, it becomes clear why such meta-representation is unattainable for movement. Even for squirrels, the number of possible next moves is so astronomically high that future projections would quickly bifurcate to infinity. Such a nonlinear system is unpredictable, rendering the calculation of hypothetical future scenarios useless. Accordingly, the combinational complexity of skilled movement, coupled with the real-time speed requirement of its production, make it impossible to micro-manage such a system explicitly. However, the explicit system can exert influence by steering events towards a strange attractor. For instance, a tennis match is a dynamic system with two moving targets. Although moment-to-moment events are completely unpredictable, the explicit system might settle to one or more strange attractors, such as the opponent's weak backhand. The explicit system can guide motor output towards such a strange attractor as long as the attractor is of a complexity that does not challenge the capacity limit.

The explicit system is thus limited to representing tasks that can be solved outside real-time and that can be broken up into chunks of complexity less than a quarternary relation. Since this is not the case for skilled movement, the implicit system must handle the skill's execution. This fact becomes important in the argument that strategic team sports, such as soccer or basketball, require a variety of prefrontal-dependent processes – planning, memory retrieval, attention, for instance – while other exercise modes, such as riding a stationary bike or running in familiar surroundings, require little, if any, prefrontal-dependent processes. The above analysis makes it clear that this is an unlikely assumption.

To illustrate that a sport such as basketball is unlikely to require activation of the explicit system and thus substantial prefrontal engagement, compare the 5-member basketball team of, say, North Carolina State University, to a 5-member (real) wolf pack hunting for a meal. In both instances, there is an overall goal, a broad strategy, a number of sub-goals that must be kept in mind, retrieval of previous memories, temporal integration, sustained and directed attention and a coordinated interplay among all five members of the group. Although these cognitive processes depend on prefrontal activation, the prefrontal cortex of a wolf appears adequate for them. It is possible to buffer, in working memory, a higher-order goal, which functions as a strange attractor – avoiding a strong tennis player's forehand, for instance – but moment-to-moment execution must always rely on implicit, reflexive loops that as a result of thousands of hours of highly dedicated practice, have the application embedded in the procedure of the task. It is these acquired motor patterns that win the day.

Because a highly-practiced skill is still performed by a conscious person, it is possible for the explicit system to partake in the skill's moment-to-moment

execution. To stay with the example of tennis, this occurs when a player buffers any part of the game – consciously reflecting on the strokes, for instance – in a higher-order representation and allows such analysis to guide movements. However, due to the explicit system's inefficiency and capacity limit, it should be obvious that any amount of transfer of the skill from implicit to explicit control gravely affects its quality. Indeed, it has been proposed that the degree of implicitness of motor competence is positively related to the quality of the performance (Dietrich, 2004a). This can be most dramatically illustrated by asking a tennis player to serve with his other arm.

The degree to which the prefrontal cortex is free to disengage from an on-going activity should depend on the amount of practice and the nature of the task, and thus the demands made by the physical activity on the prefrontal cortex. The effortful acquisition of skilled human movement recruits prefrontal, premotor, primary motor and parietal cortices as well as the cerebellum (Jenkins *et al.*, 1994). Due to the full engagement of the frontal attentional network at the time of acquisition, we are typically unable to attend to anything else (Broadbent, 1958; Cowan, 1995). It is thought that during this acquisition process the basal ganglia acts as a passive observer. However, studies have also shown that shifts in neural control occur as a function of practice so that the details of a motor task become gradually controlled by the basal ganglia (Mishkin, Malamut and Bachevalier, 1984) in a circuit that also includes the supplementary motor cortex, the motor thalamus and the hippocampus (Jenkins *et al.*, 1994). Put another way, with practice the brain builds a second, implicit representation of the task requirements which is the equivalent of what is known conversationally by the unfortunate misnomer 'muscle memory'. A thus automated motor pattern can be controlled entirely by this basal ganglia/supplementary motor cortex circuit and little prefrontal activity is required during its routine execution. This is the brain's conquer and divide principle: as the basal ganglia/supplementary motor cortex execute a complex motor skill, aided by perceptual input from the parietal cortex, attentional resources in the prefrontal cortex are no longer tied up with the details of executing the movement. Given the view that the working memory buffer of the DLPFC holds the content of consciousness and that executive attention is the mechanism to select the content (Baddeley, 1996a; Cowan, 1995), the performance of well-learned skills bypasses consciousness. This is a commonly reported experience when driving a car on a familiar route.

Thus, the more a motor skill is practised and becomes automatic, the more the details of its execution come under the control of the basal ganglia and supplementary motor cortex. Given this, an expert swimmer might more readily be able to disengage the prefrontal cortex from on-going activities than a novice. In addition, a natural movement pattern such as running, which is inherently controlled to a higher degree by the implicit system than an unnatural, complex pattern, such as swimming or tennis, might also allow for a greater amount of prefrontal disengagement. These empirical predictions deserve scientific inquiry. Also, given that the THT proposes that the beneficial effects of exercise on mood are correlated with the degree of prefrontal hypometabolism, data from such studies would lead to more individualized and thus more effective prescription of exercise routines as a

treatment for psychological disorders. To illustrate, a patient with no prior experience in aerobics would benefit less from an aerobics programme than someone who has already automatized the specific movements and can thus afford to downregulate working memory and attentional processes that engage prefrontal areas.

According to the THT, the strain on neural resources due to prolonged exercise involving the entire body results in the temporary inhibition of brain regions that are not essential to performing the exercise. Because sports involving real-time bodily motion do not require substantial prefrontal engagement, such physical activities can readily accommodate a state of prefrontal hypofunction without negatively affecting performance. It should be made overtly clear that the THT does not propose that the prefrontal cortex stops operating altogether or even is shut down to a degree that turns an athlete into an individual with mental deficits like those seen in individuals with frontal lobe injuries. The human prefrontal cortex subserves highly sophisticated functions and their detailed computation is not necessary in most instances of daily life (Dietrich, 2003, 2004b). The THT simply proposes that physical exercise relegates these highest-order computations of prefrontal circuits to a lower priority, and thus temporarily inhibits their occurrence in consciousness. It is important here that we have a clear understanding of which functions, and to what degree, the prefrontal cortex, particularly the human prefrontal cortex, does and does not control.

3.5 Reconceptualizing the existing data in the field

With this in mind, we can return to the research that has examined the link between exercise and cognitive function. By differentiating, in a categorical manner, between (1) a person who is in motion and one who is not, as for the brain this is a difference that could not be any bigger, and (2) the two different types of cognitive systems – explicit and implicit – the THT can, by offering a sound neural mechanism, disentangle the seemingly befuddling data in the field.

The THT predicts that executive processes supported by the prefrontal cortex are selectively impaired during exercise. From a common sense point of view, three minutes of moderate exercise would not be expected to produce any cognitive deficits; however, at three hours or close to total physical exhaustion, a dramatic, temporary decline of all types of cognitive performance has been documented (Cian *et al.*, 2000). Surprisingly, no empirical data exist that quantify the nature of the progressive decline that must take place.

A careful review of the empirical literature reveals that studies of the influence of exercise on cognition fall into two broad categories. In most studies, cognitive ability is evaluated at least 10–15 minutes after the exercise bout had ceased, presumably to control for some physiological confounds such as arousal. However, because of the problems highlighted above, these studies cannot be taken as indicative of cognitive ability during exercise. In an EEG study using exercising cats, for instance, Ángyán and Czopf (1998, p. 267) reported that 'during rest, the pre-running brain activity gradually reappeared'. It is clear then, especially in light of the THT, that studies using

a delay cannot be used to interpret cognition during exercise. In the second category, cognitive ability is tested during exercise (for reviews see, Brisswalter, Collardeau and Arcelin, 2002; McMorris and Graydon, 2000; Tomporowski, 2003b); however, the cognitive tasks typically used in these studies have so far been limited to implicit tasks, such as basic choice reaction time and/or visual recognition tasks. Implicit tasks such as these do not tap into changes in higher cognitive abilities that occur during exercise.

This led us to conduct a study, which, to our surprise, had not been attempted before. Our aim was to assess, during exercise, cognitive processes supported by the prefrontal cortex, such as working memory, executive attention and response inhibition. Using putative neuropsychological measures that are sensitive to prefrontal impairment, such as the Wisconsin Card Sorting Task, the Paced Auditory Serial Addition Task or the Stroop Test, we predicted that an individual's ability to perform tasks known to heavily recruit prefrontal circuits should be selectively impaired during endurance exercise, while tasks requiring little prefrontal activation should be unaffected. Our results showed that this is indeed the case (Dietrich and Sparling, 2004), indicating that a 'noncognitive' task, such as running on a treadmill, can constrain resources available for cognition. Following our initial study, there are now several other laboratories that have reported cognitive impairment in executive tasks during exercise (Audiffren *et al.*, in press; McMorris *et al.*, 2008b).

Our results seem to run counter to the general consensus in the literature (McMorris and Graydon, 2000; Etnier *et al.*, 1997) that exercise produces an enhancement, albeit mild, of cognitive performance during and after exercise only if one fails to distinguish between the implicit and explicit processing systems. In a similar vein, our results appear contradictory to the data showing that executive functions are spared in aging for individuals leading an active lifestyle (Colcombe and Kramer, 2003), only if one fails to factor in the difference between acute and chronic exercise.

Here, then, is, if you allow for a little embellishment, what seems to be going on. As a person starts the kind of physical activity that requires large muscle groups for sustained periods of time, say, playing tennis on clay, the brain shifts its metabolic resources to adequately drive the motor neurons. Within minutes, apparently, given the data (Kemppainen *et al.*, 2005; Tashiro *et al.*, 2001), this has profound consequences for those neural regions whose computations do not contribute to the on-going activity. As hypofrontality sets in, two things happen. First, information processing in the explicit system is inhibited due to a lack of resources to prefrontal regions. This, as I pointed out above, is not a problem, even for supposedly strategic sports. Second, information processing in the implicit system, now disinhibited from explicit control, is enhanced. This results in faster responding and more accurate play. It is not difficult to see how this set of circumstances is advantageous from an evolutionary point of view, as strenous physical activity typically occurs in the animal kingdom in 'do-or-die' situations where a faster and slightly more accurate decision-making ability, at least in binary choice situations, can make all the difference.

In addition, either as a direct consequence of the hypofrontality, as this might lead to the disinhibition of lower brain regions, or due to an entirely different mechanism,

the arousal system in the brainstem is activated. This results in the upregulation of several neurotransmitter systems, which might further enhance implicit task performance. Given the research on the effects on cognitive function under stress (Beilock and Carr 2005), arousal does not seem to enhance explicit task performance. Unfortunately, we have no space to delve any deeper into these neurochemical mechanisms in this chapter and I put them aside for now.

As the person continues the physical activity, the brain's position, in terms of its metabolic resources, is becoming increasingly precarious. In order to keep the motor neurons firing at the rate required to maintain the intensity, the brain is driven deeper and deeper into a metabolic hole. It is forced, then, to downregulate additional neural networks. This process continues down the functional hierarchy of the brain until eventually, near exhaustion, this has also negative consequences for the implicit system to process information. Unfortunately, there is not enough empirical data to precisely describe this relationship, that is, how, exactly, the initial facilitation and the subsequent decline of implicit task performance proceed as a function of the computational demands of the exercise. Although the existing data meshes well with this conceptualization, further, systematic – theory-driven, that is – research efforts are clearly needed in this area.

I might interject here a brief mentioning of another effect of exercise on cognitive functioning. It seems obvious that the prolonged disengagement of higher cognitive centres in the prefrontal cortex due to *endurance* exercise bears on the exercise-induced alteration of consciousness known by the misleading descriptor the 'runner's high'. Here the THT also offers a novel mechanistic explanation, as some of the phenomenologically unique features of this state, such as analgesia, euphoria, sensations of timelessness, ephemeral attention, a state of silent introspection and reduced awareness of one's surroundings, are consistent with a state of prefrontal hypofunction (Dietrich, 2003; Dietrich and McDaniel, 2004).

Consider, for instance, this experience reported by Vito Bialla (2002) during the Badwater Ultramarathon: 'As I bend over to stretch, I look at the pavement and there are thousands of bats flapping their wings, all in 3-D. I pee in the sand, and the entire ground turns into living plant life moving up to knee-level. Everything around me is in motion. I hallucinate for the next 8–10 hours. During the night I experience the most fantastic visual experience I've ever witnessed. Plants and bushes turn into dinosaurs snapping at me as I go by. I see pianos and furniture in the middle of the road. Physically, I'm fine, but the visual deserves an Oscar'.

Irrespective of this, in all but the most extreme cases, the person stops the exercise well short of exhaustion and the compensatory mechanism proposed by the THT ends up affecting only a few brain regions, such as the prefrontal cortex. It is for this reason that I named the theory the transient hypofrontality theory. At exhaustion, however, the hypometabolism is likely to be more widespread, reaching beyond prefrontal regions, as evidenced by the impairment seen on all types of cognitive tests at that time (Cian *et al.*, 2000). Ultimately, for people so fit that they have not yet succumbed to peripheral fatigue – muscle failure, to be precise – and who continue to exercise, the brain's very ability to even drive the motor neurons itself might be

compromised. This, however, is yet another implication of the present theory – its relationship to the concept of central fatigue – that we must leave for another time.

If, on the other hand, the person stops the exercise, matters return back to normal. In this case, unless you are committed to dualism holding out for some kind of ghost in the machine, you must concede that the motor neurons driving the motion return immediately back to baseline firing rates; otherwise, the person would still be moving, as it is these very neurons that control the motion in the first place. You might argue here that in mental imagery one recruits the same kind of brain circuits that are recruited when the imagined task is actually performed and, therefore, the neuronal activity might not immediately return to baseline. It should be clear by now, though, that movement and imagined movement are not at all the same, neither, at the very least, in amount of neural tissue activated nor in the intensity of the activation. If they were, you would be moving every time you imagined moving. This does not preclude, of course, the fact that the mental representation of movements is coded in neurons that also take part in the actual execution of the movement. It is conceivable, for instance, indeed quite likely that it might take the brain some additional time to redistribute the metabolic resources back to pre-exercise levels even though the motor neurons are no longer in need of excess amounts of them.

Either way, the empirical data show a facilitation effect *post*-exercise on implicit task performance (Brisswalter, Collardeau and Arcelin, 2002; McMorris and Graydon, 2000). For the THT, which is designed to account for phenomenological changes during exercise, post-exercise data fall outside the domain it claims to cover. Although the THT might still inform mechanistic explanations of these post-exercise effects, any such explanation is speculative at this time. One can imagine, for instance, that the disinhibition of lower brain regions caused by prefrontal hypofunction continues for some time. Little is known about the time it takes the brain to resume pre-exercise status, data that should inform any attempt for a mechanistic explanation for these effects. Alternatively, one can imagine that the reduction in anxiety, which is known to linger, helps to facilitate cognitive function. It seems, then, that neurochemical theories, especially as they relate to arousal, are better candidates for a neural mechanism of the lasting psychological effects of exercise.

This is also the case for the sparing of higher cognitive function in aging that is associated with long-term exercise intervention programmes (Colcombe and Kramer, 2003). Because these kinds of long-term effects necessarily require structural changes to the nervous system, theories at the molecular level make for better explanations of the neural mechanisms involved (van Praag *et al.*, 1999; Cotman and Engesser-Cesar, 2002). There might be a link here to the THT as well, though. Chronic stress produces higher levels of glucocorticoids, which are known to cause accelerated neuronal death (Sapolski, 1992). Prefrontal neurons seem to be particularly susceptible to this. Exercise, then, might not only reduce the stress response but also check excessive activity in prefrontal neurons, which, over a lifetime, might be neuroprotective for these neurons. Again, considerably more research needs to be done in this field, especially the kind of research that is informed by current frameworks of neuroscience and cognitive science.

4

Methodological issues: research approaches, research design, and task selection

Phillip D. Tomporowski

Everyone knows that exercise is good for the mind. Indeed, beliefs concerning the psychological benefits of exercise can be traced to antiquity. In the past few decades, literally thousands of publications appearing in the general press and in the media have proselytized the beneficial effects of exercise on mental processes. Educators and parents know that exercise is good for the mental development of children; older adults are confident that routine physical activity will ward off the vicissitudes of nature.

Research scientists, however, are trained to weight the strength of the evidence before lending support to relations that exist in nature. This caution reflects academic training in a philosophy of science that emerged in sixteenth and seventeenth century Europe and the rules of research conduct articulated by such thinkers as Sir Francis Bacon (1561–1626) and Sir Isaac Newton (1642–1727). Central to the scientific method is the notion that reality emerges only from observable proof. Sir Francis Bacon's brand of positivism, for example, warned of sources of errors in scientific investigation that could be attributed to the 'idols of the cave', in which a researcher's perspectives are influenced by personal biases; 'idols of the tribe', when a researcher attends selectively only to data that confirm his or her wishes and desires; 'idols of the marketplace', in which words, rather than measures, bias researchers' perceptions of nature; and, lastly, 'idols of the theatre', in which a researcher can become entrenched in a single view of nature (Hergenhahn, 1992).

The methods of science that guided the development of the fields of physics, chemistry and astronomy provided the framework for modern scientific psychology developed in the early twentieth century (Gregory, 1981). Psychologists of the period

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who discussed issues related to research methodology often implored behavioural and social scientists to strive to achieve the ideals of the more mature physical sciences and to study psychological phenomena with empirical rigour. Early psychologists were acutely aware of the difficulties that confront behaviour and social science, however. As stated by Benton Underwood (1957), 'probably, there is no other area of human endeavor which so badly needs a thoroughgoing application of the scientific method as does psychology, for probably in no other area are there so many misconceptions, half-truths, and abortive attempts to understand behavior (p. 1)'. The comments made 50 years ago ring true today. Contemporary researchers must constantly inspect and review methods employed to describe and explain psychological phenomena.

The central purpose of science is to reveal relations in nature. The authors who have contributed to this text attempt to describe and understand the relation between exercise and cognition. Until relatively recently, there were some who questioned the linkage (Tomporowski and Ellis, 1986; Tuckman, 1999). In the past few years, however, a number of studies have been published that support the prediction that both single bouts of exercise and systematic exercise training modify cognitive function in adults (Brisswalter, Collardeau and Arcelin, 2002; Colcombe and Kramer, 2003; Etnier *et al.*, 1997; Tomporowski, 2003b) and children (Sibley and Etnier, 2003; Tomporowski, 2003a). As evidence accumulates, it is incumbent for researchers in the field to: (1) evaluate the results of prior research evidence in light of the research methods employed; (2) design studies that provide an unambiguous description of the relationship; and (3) explain how exercise impacts cognition.

The goal of this chapter is to reiterate the basic framework of psychological research described by numerous social scientists. The chapter consists of three parts. The first addresses research approaches that can be taken to study the relation between exercise and cognition, the second delves into topics that focus on research validity and the third addresses the diversity of outcome measures available to researchers. The chapter concludes with a commentary concerning future research and theory development.

4.1 Research approaches

Many psychologists in the early twentieth century eagerly embraced the research approaches employed by scientists in physics. The monumental theory developed by Clark Hull (1884–1952) provides, perhaps, the clearest example of an explanatory system of psychological phenomena based on direct observation and measurement. Hull followed the deductive method used by Newton to develop a theory applied to all mammalian behaviour (Hull, 1943). The theory involved the postulation of intervening variables such as drive, habit strength, and incentive to account for observable events. Predictions derived from the theory led to many empirical experiments and it shaped the research approach employed by many generations of subsequent researchers (Lundin, 1985).

It is important not to lose sight of the historical ties that link contemporary research approaches to those selected in the past. While modern science appears on the surface to be more sophisticated than in the early decades of psychological research, the methodological challenges faced by Clarke Hull and other researchers of psychology's early era (e.g. Edwin Guthrie, Edwin Tolman and Kenneth Spence) have not changed. Understanding relations that exist between exercise and cognition hinge on two conditions: (1) operationally defined psychological constructs and (2) developing methods that allow researchers to summarize and explain observations of the exercise-cognition relationship.

Operational definitions in psychological science

Researchers who study the relation between exercise and cognition make use of constructs such as memory, inhibition, attention, executive function and so forth. Terms such as these have both 'dictionary' meaning and 'scientific' meaning, and how they are used differentiates scientific from nonscientific approaches to understanding a given phenomenon. Normal discourse involves the selection of words from our language system to communicate a general level of meaning. Scientific communication is guided by a set of rules designed to ensure precision of the definition of terms. Providing an *operational definition* of a construct under investigation is a pre-requisite to understanding the phenomenon. An operational definition is one which specifies the meaning of a concept by denoting measurement operations (Underwood, 1957). Such a definition differs from a general 'dictionary' definition for a term in that it is linked to measurement procedures that produce observable and reliable outcomes. The construct 'weight', for instance, is operationally defined in terms of values obtained from a scale.

Restricting scientists to the use of operationally defined terms benefits the research community. Constructs defined operationally facilitate communication among researchers by reducing or eliminating misinterpretations. Further, operational definitions reduce the redundancy inherent in the terminology used by researchers. When a given construct is defined via direct observation and measurement, it clarifies both similarities and differences that exist between and among constructs. As a result, operational definitions restrict the number of concepts available for use within a particular domain or investigation.

It is incumbent upon researchers who study the exercise-cognition relation to employ terms that describe operationally what they mean by use of the term, 'exercise' as an independent variable, and what they mean by the use of the term, 'cognition' as a dependent variable. When used in general discourse, the terms may conjure up meanings that may differ considerably among individuals. The value of tying concepts to measurement procedures is that it results in greater communication among researchers.

While researchers strive toward the attributes associated with the ideals of the scientific methods, the reality is that considerable ambiguity exists among many of the constructs selected to assess the effects of exercise on cognition. Young

researchers drawn to the study of exercise and its effects on mental function are faced with a bewildering number of constructs from which to choose. Further, disagreements still exist among researchers as to how a particular construct is defined. Executive function, which is discussed in many of the chapters in this text, provides the illusion of being a clearly defined construct. Indeed, tasks have been identified that measure such constructs as shifting (processes involved in switching between mental sets), inhibition (processes involved in the suppression of dominant or pre-potent responses) and working memory (updating and monitoring memory representations) (Miyake *et al.*, 2000). On closer inspection, however, the measurement procedures used to define each construct may differ from one research group to another. Mental shifting, for example, for some researchers involves processes required to disengage from an irrelevant mental task and to engage in the performance of a relevant task (see Monsell and Driver, 2000). Shifting is proposed to be regulated by structures in the prefrontal cortex. This conceptualization of the construct of switching, however, is not the same as that used by those who use the term switching to refer to visual disengagement from a fixation point to the spatial location of a predicted target stimulus (Posner, 1980). The control of this form of visual switching is hypothesized to be regulated by parietal and mid-brain areas (Posner and Dahaene, 1994). Similarly, the construct of inhibition has been defined in terms of measures obtained from tests such as the Stroop, antisaccade task and the stop-signal task. Inhibition processes are hypothesized to be central to the control of the production of a dominant or automatic response (Dempster, 1995; Logan and Cowan, 1984). Response inhibition is believed to involve structures in the prefrontal cortex. However, inhibition is also used to describe a decrease in the level of activation seen in tasks that employ negative priming procedures, which involve using a target stimulus on one trial that has been employed as a distractor stimulus on a previous trial (Tipper, 1985, 2001; Tipper and Cranston, 1985). Lastly, the construct of working memory is measured via tasks that involve updating processes. This conceptualization of working memory, which focuses on the ability of an individual to manipulate relevant information, draws from neurophysiological research that links task performance to specific regions of the prefrontal cortex. However, other researchers assess short-term memory processes that are central to the encoding, storage and retrieval of information. The brain structures implicated in these processes include the pre-motor areas of the frontal cortex and the parietal lobes (see Baddeley, 2007; Shah and Miyake, 1999b for overviews).

Presently, there is a lack of agreement concerning the operational definitions of most of the constructs used by researchers in the field (see Ericsson and Delaney, 1999). However, this lack of precision might be expected for psychological science, which is a relatively young domain of inquiry. One of the challenges facing contemporary researchers and for future generations of researchers will be to sharpen the definition of the mental constructs used in theory development.

Description and explanation of the exercise-cognition relation

Early philosophers of science provided a formalized list of 'stages' of understanding. The initial stage of understanding a phenomenon involves employing direct observation, which may lead a researcher to *describe* relationships that exist between events. Cultural anthropologists, for example, attempt to understand why past civilizations thrived and then collapsed by directly examining cultural artifacts, data concerning climatology, historical evidence, and so on. Exercise psychologists, likewise, depend upon direct observation of the relation between physical activity and mental function. Unbiased, direct and reliable observations provide the keystone for all other stages of understanding. Repeated demonstration that one event (exercise) reliably leads to another event (cognitive function) provides the basis for the next stage of understanding – laws. The bedrock of experimental psychology was the study of psychophysics. Through careful and systematic experimentation, researchers measured the relation between alterations in environmental stimuli (e.g. sound wave amplitude) and participants' reports of sensory experiences (e.g. loudness). The consistent results obtained from many experiments led to explanations of psycho-physical relations in terms of mathematical equations (e.g. the Weber–Fechner Law) that not only described but predicted how mental processes change as a function of the environmental stimulation. The Borg Scales (Borg, 1998), which are used extensively by exercise scientists, provide examples of lawful relations between physical activity and perceptions of exertion. There are few phenomena studied by exercise psychologists that can be explained in terms of laws, however.

Several approaches can be used to *explain* relations between exercise and mental functioning. Some researchers use *models* to explain specific phenomena. Detailed overviews of psychological models and how they can be used to help researchers explain an area of study are available in the literature (Underwood, 1957). A common element articulated in these presentations is that models are used to understand the unknown in terms of the known. Indeed, the seminal publication, *Plans and the Structure of Behaviour* (Miller, Galanter and Pribram, 1960) explained how the functions of the mind (i.e. the unknown) might be understood in terms of the operation of a simple computer (i.e. the known). The information-processing model, which has had a tremendous guiding influence on cognitive psychology, plays a central role for some researchers in understanding how exercise influences cognitive function (see Chapter 1). Models are particularly useful for researchers who are investigating a relatively new phenomenon, such as the exercise-cognition relationship. Explanatory models provide researchers with both the means to organize observations of behaviour and a 'starting off' point for conducting research. As research in the field matures, however, and knowledge accumulates, the need for models may decline and be replaced by other explanatory approaches.

Intervening variables and hypothetical constructs

Intervening variables and hypothetical constructs are commonly used by cognitive scientists. Indeed, the aforementioned constructs of executive function (shifting,

inhibition and working memory) provide examples of terms used by researchers relying on these two approaches. Intervening variables are words, not real things; they are hypothetical internal states constructed to explain relationships between observed variables, such as exercise and cognitive test performance. Several experimenters have reported that acute bouts of physical activity alter individuals' performance on the colour-naming condition of the Stroop task (Sibley, Etnier and Le Masurier, 2006). This relation between the manipulation of exercise demands and cognitive test performance has been explained in terms of the role of the construct, 'inhibition', a state within the individual that cannot be observed directly, but that nevertheless links observed changes in environmental conditions to changes in test performance. Intervening variables are very useful; they help researchers summarize observations reported in individual experiments. Care, however, must be taken by researchers to ensure that a given intervening variable is not assigned a causal role in explaining behavioural change; to do this is to engage in circular reasoning (see Underwood, 1957, p. 202–213).

Researchers who link psychological constructs to underlying physiological structures and functions explain phenomena in terms of hypothetical constructs. Often hypothetical constructs are created that implicate structures hypothesized to play a role in explaining a given relationship but whose existence has yet to be empirically demonstrated. Donald Hebb (1949), for example, hypothesized in the 1940s that learning could be explained in terms of the timing of activation of networks of neurons. The existence of these neural networks remained hypothetical constructs until decades later when the development of new neurophysiological measurement techniques provided the means to confirm Hebb's hypothesis. Thus, it is the emphasis on real physiological processes that differentiates hypothetical constructs from the abstract, explanatory concepts of intervening variables.

Advances in behavioural neuroscience over the past two decades have brought much desired clarity to the workings of the central nervous system. Techniques such as magnetic imaging, positron emission tomography, transcranial magnetic stimulation, together with established methods such as electroencephalography, and event-related potential, provide contemporary researchers with an increasingly large arsenal of tools to use to study brain function. The level of analysis of neurophysiological function has also changed; for example, measures are now available that describe the operations of individual neurons at a molecular level. The 'zeitgeist' of contemporary exercise psychology is clearly one of *physiological reductionism*; that is, positing explanations of psychological phenomena in terms of progressively more refined measures of physiological processes. Indeed, some exercise psychologists suggest that our understanding of psychological phenomena lies exclusively in understanding brain physiology (Acevedo and Ekkekakis, 2006). Historically, similar ideas were expressed in the late nineteenth century by the physiologist Hermann von Helmholtz who, with his colleagues, ascribed their acceptance of physical monism by signing a declaration in their own blood (Hergenhahn, 1992)! Fortunately for contemporary researchers, the decision to explain psychological phenomena in terms of an intervening variable or a hypothetical construct does not require a

life-long commitment to one approach or the other. Debate concerning the merits of the two explanatory approaches has been ongoing for decades and will, in all likelihood, continue. It may behove contemporary researchers to appreciate that evidence accumulated from the two approaches converges and provides the basis for a deeper theoretical understanding of the relation between exercise and cognition.

Theories

Theories provide the most abstract stage for understanding a phenomenon. Philosophers of science have discussed theory development in great detail and the role that theories play in research (e.g. Kuhn, 1973; Popper, 1968). Several themes emerge from these various presentations. A theory is an abstract explanation for facts that exist in a domain of inquiry. The inductive method of inquiry is used to organize information and to provide a general summary statement. A theory attempts to provide a deeper understanding of a phenomenon than can be achieved through use of a descriptive law or construct. A theory also provides explicit predictions about the results of studies that have yet to be performed. The deductive method of inquiry is employed to generate testable experimental hypotheses. Deduction is a method of reasoning in which a general case leads to the prediction of a specific outcome. An important characteristic of any theory is that can be falsified (Popper, 1968).

Induction is a method of reasoning in which a number of individual observations are synthesized into a general statement. As shown in Figure 4.1a, a theory begins when a scientist notes linkages in the results of studies conducted in different domains. A close examination of the facts, laws and constructs gathered in various areas of research are compared and contrasted. From these findings, the theorist develops a set of *coordinating definitions*, which are used to help describe commonalities that exist among, what may appear, at first glance, to be unrelated areas of investigation. The next step in theory development is the presentation of a basic principle or set of principles that conform to established facts and laws. As shown in Figure 4.1b, a theorist can then generate hypotheses that allow for direct tests that will establish the validity of the theory. Theory testing is critical for determining the usefulness of a given theory.

The criteria required for an explanatory system to be classified as a theory are reasonably well established. Care should be taken by researchers to differentiate between scientific theory and lower stage descriptions of specific phenomena. Young researchers are often advised to develop 'theory-driven' research only to be overwhelmed by the sheer number of theories that are viable. The advice that has been given for decades to young researchers is to select a theory that makes 'good sense' and to conduct well-designed experiments to test specific predictions (Underwood, 1975). There are a number of useful theories that have been called upon to explain various aspects of cognition (e.g. Baddeley, 1986; Kahneman, 1973; Sanders, 1998). An excellent example of comparing and contrasting theories of working memory and executive control is provided by Miyake and Shah (1999b). At this time, no one theory

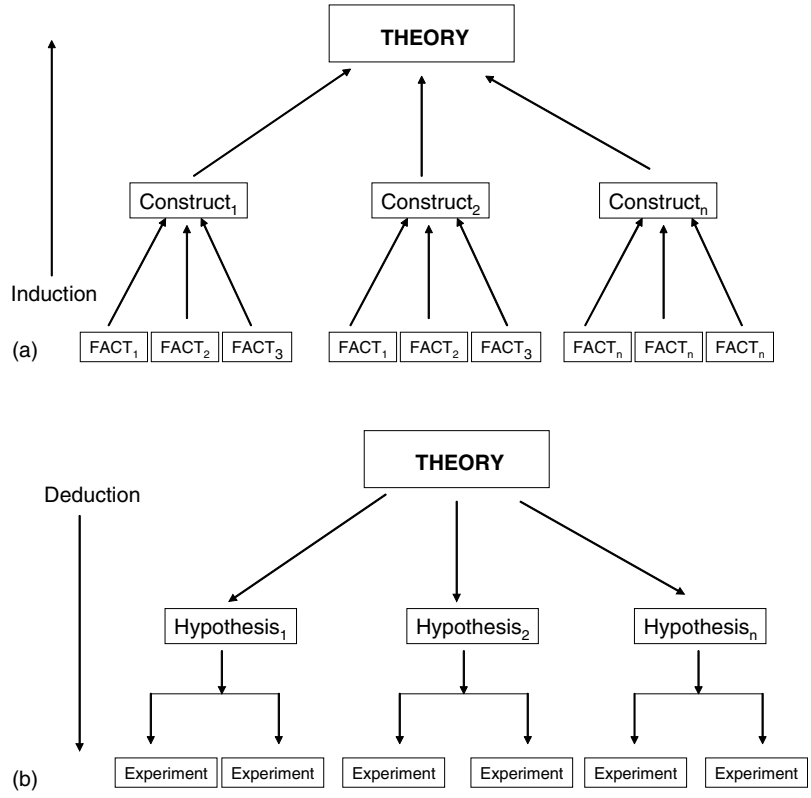

Figure 4.1 (a) The method of induction: a method of reasoning in which a number of individual observations are synthesized into a general statement. (b) The method of deduction: a method of reasoning in which a general case leads to the prediction of a specific outcome.

has been proposed that addresses explicitly the relation between exercise and cognition. However, several hypotheses concerning the relationship between exercise and cognition have recently been proposed that are useful guides for contemporary researchers (e.g. Dietrich, 2003; Kramer *et al.*, 2002).

Individual differences among research scientists

Explanations of natural events become progressively more abstract as one moves from one explanatory stage to another, passing from description, laws, intervening variables, and hypothetical constructs on to theory. Scientists are faced with the reality that the explanations they generate may be wrong. As human nature reveals, some individuals are more willing to be found wrong than are others. Researchers who limit their activities to simple descriptions of relations that occur in nature and who conduct direct and systematic replications of their experiments are less likely to be wrong than researchers who develop abstract hypotheses concerning complex multivariate relations. Importantly, one stage of explanation is not 'better' or 'more

important' than another stage. Researchers can spend their entire academic career explaining nature at a descriptive level and have profound effects on science. Not all scientists have the desire or interest in developing psychological theories. Further, there is nothing to impede an individual from shifting back and forth from one stage of explanation to other stages throughout his or her career. There is, and will continue to be, a need for researchers to conduct work at each stage of the explanation continuum.

Historians of science have discussed in detail factors that influence researchers in a given field of study. Thomas Kuhn (1973) argued that researchers are primarily 'puzzle solvers' who are interested in 'figuring out' natural phenomena. During the early pre-paradigmatic stages of scientific inquiry in a given field, different researchers examined the same phenomena with different methods and interpreted observations in different ways. Over time and with competition among different schools of thought, a standard research approach emerged that led to a period of normal science, which was characterized by adherence to an accepted theory. Clearly, contemporary research conducted in the field of exercise and cognition is pre-paradigmatic.

4.2 Research design issues

Nascent scientists are introduced to many techniques and procedures used to conduct naturalistic observation and experimentation. Requiring students to undergo years of academic training ensures that the facts they obtain are interpreted wisely and in accordance with certain principles. The methods that are employed early in a researcher's career become more sophisticated with time and experience. Indeed, the developments in quantitative psychology continually infuse new methods for analyzing data sets. However, regardless of the intricacies of emerging research tools, the goal of scientific research is to acquire valid measures of phenomena that occur in nature.

The methodological rigour of research conducted to assess the relationship between exercise and cognition varies considerably. As a result, interpreting the usefulness of the results from many studies has been challenging for researchers who have employed quantitative and narrative approaches. Over the past decade, there have been an increasing number of studies conducted to evaluate the exercise-cognition relation. As interest in the phenomenon increases, it will be important for researchers to keep in mind the importance of conducting studies that provide useful information; that is, information that provides a valid assessment of the relation between a variable that is manipulated and a variable that is measured. In keeping with the spirit of the preceding section of this chapter, it is considered important for researchers, regardless of the stage of their careers, not to lose sight of guidelines that have been established for conducting valid and useful studies.

Many textbooks have been published that address research design and measurement issues (Elmes, Kantowitz and Roediger, 2003; Kerlinger, 1986; Kirk, 1995;

Lehman, 1991). The classic monograph *Experimental and Quasi-experimental Designs for Researchers,* by Campbell and Stanley (1966), is recommended for its concise description of challenges that face contemporary researchers. Described next are several topics that are particularly relevant for researchers who strive to attain an unambiguous understanding of the effects of exercise on cognition.

Exercise as an independent variable

Exercise is defined as a 'subset of physical activity consisting of planned, structured, repetitive bodily movements with the purpose of improving or maintaining one or more components of physical fitness or health' (Dishman, Washburn and Heath, 2004). As reflected in the outline of this book, two lines of research have dominated the field. A number of researchers have focused on measuring the effects of acute exercise on cognition and employ study designs that employ a single, relatively short-lived bout of exercise. Research studies conducted in the 1970s and 1980s tended to focus on the impact of aerobic exercise on cognitive function and employed protocols in which participants ran or cycled continuously for over 20 minutes. The rationale for the selection of this particular intensity and duration was prompted mostly by anecdotal reports that mental concentration and attention improved during and immediately following steady-state jogging (Mandell, 1981; Sachs, 1984). Few of the exercise protocols employed in the early laboratory studies were linked explicitly to physiological changes that accompany physical activity. More recently, the roles of exercise type, intensity and duration on cognitive function have drawn the attention of researchers. Contemporary researchers are challenged to assess how specific exercise conditions differentially influence particular cognitive functions. Consider that the thrust of many of the chapters in this text is directed toward describing how acute bouts of exercise facilitate cognitive functions. It will also be important for researchers in the field to evaluate systematically how exercise-induced fatigue develops and compromises mental functioning and decision-making during and following exercise (see Hockey, 1997).

Researchers have also focused on chronic exercise training and how it influences cognitive function. Chronic exercise is defined as multiple bouts of physical activity performed repeatedly over time, usually several times each week for various durations (Buckworth and Dishman, 2002). Research on exercise training in the 1970s and 1980s was driven by the proponents of the 'wellness' movement, emergence of the academic field of health psychology and interests in interventions that might offset age-related declines in cognitive function (Folkins and Sime, 1981). The vast majority of published studies have employed aerobic training as the exercise intervention. The assumption has been that routine exercise improves cardiorespiratory function, which, in turn, facilitates brain functions that underlie mental processes. In many of these studies, measures of cardiorespiratory function have been presented as the 'gold standard' to quantify the impact of exercise training. Recently, the merits of this assumption have been questioned in a quantitative review of studies that provided indices of the strength of the relation between change in cardiorespiratory

capacity and cognitive function (Etnier *et al.*, 2006). While it is clear that chronic exercise interventions modify cognitive function, it is not entirely clear what aspects of the exercise intervention drive these changes. Across the various published studies, the types of aerobic exercise employed vary as does the frequency and intensity of training. Further, the impact of factors other than exercise (e.g. social interactions, skill development, motivation and attention) is seldom controlled. Progress in understanding how chronic exercise training influences cognitive function will hasten when researchers provide, not only detailed descriptions of the exercise interventions employed, but also information concerning the instructional environment.

The vast majority of studies that examined the effects of chronic exercise on cognition employed research designs in which cognitive tests were administered prior to and following an exercise intervention of a specific duration. Historically, the length of exercise training was selected to ensure that the intervention produced an improvement in physical fitness, typically cardiorespiratory function. In actuality, relatively little is known about the time course of cognitive change. Recent advances in our understanding of how physical activity modifies brain function at the neuronal level (Vaynman and Gomez-Pinilla, 2006; Vaynman, Ying and Gomez-Pinilla, 2004) suggest that the effects of exercise may occur relatively rapidly, perhaps within a few bouts. Information concerning the rate of change in cognitive function with repeated exercise bouts is much needed. Likewise, virtually nothing is known about the degree to which improvements in cognitive function are maintained following the termination of exercise training. Answers to questions concerning the amount of exercise required to induce change in cognitive function and the durability of those changes are important for both applied and basic research scientists.

In summary, exercise behaviour is complex and it can be manipulated in terms of type, duration and intensity. The manner in which cognitive function is influenced by exercise is, in all probability, related to these variables.

Obtaining valid measures of the effects of exercise on cognitive function

Scientists strive to make truthful and valid observations of relationships that exist in nature. The validity of research conducted to assess the exercise-cognition relation can be interfered with, or confounded, by a variety of conditions. A confounder is an extraneous factor that is not an experimental manipulation that distorts the interpretation of an observed relationship between the independent and dependent variables. Confounders can compromise both a study's internal validity, that is the ability to show a cause–effect relation, and its external validity; that is the degree to which observations can be generalized to other situations or individuals. Factors that influence the interval validity of a study include a series of factors, which are described below.

(a) *Testing* The majority of published studies that have examined the exercise-cognition relation have used research designs in which participants complete

a cognitive test before and following an exercise intervention. Change in performance is typically attributed to the effects of exercise. There are, however, factors other than exercise that may explain these changes in performance. For example, participants' familiarity with the task may change across testing conditions. The tasks that participants are asked to perform are, for the most part, novel and unpractised. It is well known that performance of novel tasks, even the simplest ones, improves with practice (Spirduso, 1975, 1980). If participants are not provided sufficient practice, changes that are observed following an exercise intervention may be a reflection of continued task practice rather than the effects of physical activity. Researchers who select cognitive tasks that measure speed of processing should be particularly sensitive to the role of practice on experimental outcomes. Several authors have addressed the shortcomings of insufficient practice and suggested ways to reduce its impact (Salthouse and Hedden, 2002). Similarly, researchers who select cognitive tasks that involve multiple mental processes need to be cognizant that the task's pre-test performance may prime the participant's post-exercise test performance. The experience of, and memory for, performing mathematics calculations during pre-testing, for example, may educe mental operations and strategies that facilitate performance during post-testing, irrespective of exercise.

(b) *Instrumentation* Researchers sometimes administer alternative test forms to reduce possible confounds that result from using identical pre- and post-exercise tests. However, care should be taken to ensure the equivalence of the tests employed. It is also the case that the research equipment used to collect data may change subtly yet significantly over time, requiring recalibration.

(c) *History* The delay between pre- and post-testing may provide participants the opportunity to be influenced by factors that are not related to the exercise manipulation and these experiences can influence post-exercise test performance. Researchers who evaluate the effects of acute bouts of exercise on cognition often employ nonexercise control conditions in which the participants 'rest'. The 'rest' condition does not, however, preclude the possibility that the participant will be influenced by factors that influence later cognitive test performance. For example, conditions that require individuals to sit quietly and do nothing may elicit boredom and a negative affect; alternatively, nonexercise conditions that permit participants to read or watch a video may elicit affective changes. Regardless, experiences during nonexercise control conditions can lead to changes in task performance that differ from those obtained following exercise, leaving the possibility that performance differences are due to the effects of the nonexercise control condition on performance rather than to effects of exercise as an independent variable (see Morgan, 1997). The threat of participants' history on post-test performance is particularly vexing for researchers who assess the chronic effects of exercise on cognition. Considering that exercise interventions can last for several months, participants in both experimental and control conditions have an opportunity to be

influenced by numerous nonintervention experiences that can influence cognitive test performance. Participants cannot be made unaware that the exercise programmes are designed to influence their mental functioning and, as a consequence, they may seek ways to improve their cognitive performance independently of the exercise intervention.

(d) *Maturation* Human capabilities change with the passage of time. The physical and psychological changes that transpire from birth to early adulthood are remarkable. So too are age-related changes in capability across the adult lifespan. Care must be taken by researchers who assess chronic exercise interventions to take into account the degree to which changes in outcome measures are attributable to an exercise intervention and changes that can be explained in terms of normal cognitive development.

(e) *Sampling* The internal validity of a study can be compromised from the biased selection of research participants. It is not unusual for individuals who view themselves as physically fit to be more likely to volunteer for an exercise-related study than those who perceive themselves to be less physically fit. Researchers should take care to ensure that all individuals selected for research have an equal opportunity to be assigned to an experimental or control condition. The goal of achieving unbiased participant sampling is particularly difficult to achieve when studies are conducted with individuals with unique characteristics; for example elite athletes.

(f) *Mortality* Participants sometimes withdraw from research studies. The interpretation of results obtained from studies can be jeopardized if the number of individuals who drop out is not equally distributed across groups. Exercise-related studies are particularly prone to subject attrition, with individuals who are less physically fit being more likely to depart than those who are more fit. Besides affecting the degree to which the results of the study can be generalized to the general population, the asymmetric selection of individuals is problematic for statistical analyses and interpretation.

(g) *Statistical regression* A central tenant of psychometric test theory is that the distribution of the scores obtained when a test is administered to a population of individuals will approximate the normal curve modal. Under conditions in which a researcher draws a sample of individuals who have either very low scores or a sample with very high scores and then re-administers the test, the average performance of the low-scoring group will be higher on the second test and the average performance will be lower on the second test for the high scoring group. In both instances, the groups display a statistical phenomenon referred to as regression toward the mean. Statistical regression results from an asymmetrical sample of a population. The confounding effects of statistical regression are not a problem when researchers obtain a random sample from a population; the phenomenon becomes problematic when purposive sampling procedures are employed that identify individuals who are either very poor or

very high performers. The issue of statistical regression is of particular importance for researchers who are interested in individual differences that involve assessing low- and high-performing individuals. The topic of statistical regression has been discussed extensively (Shephard, 2003; Smith and Smith, 2005), and several methods are available for estimating and correcting regression to the means (Campbell and Kenny, 1999).

External validity

External validity reflects the degree to which the results obtained in a study generalize to other conditions and people. Factors that influence the external validity of a study are discussed below:

(a) *Interaction of participant selection and treatment* Nonrandom subject selection can result in a study conducted with participants who have particular demographic or organismic characteristics that may bias their performance. Reviews of acute-exercise studies reveal that many have been conducted with college-aged, young adults often drawn from undergraduate classes predominated by students with interests in physical activity or health. Further, most chronic-exercise studies have been conducted with older adults who are often selected from university-related physical activity programmes. Thus, selection bias is an issue in the vast majority of studies that have been conducted. As research in the field advances and resources become available for large-scale studies, it will be important for studies to include a broad spectrum of participants.

(b) *The situation in which the study is conducted* The manner in which participants react to the setting in which the study is conducted may influence their performance more than the intervention itself. Researchers cannot escape the fact that the participants in studies conducted with humans must deal with social interaction threats. People who volunteer to participate in research enter with pre-conceived expectations and beliefs. The fact that participants are aware that their behaviours are being monitored and evaluated may lead them to engage in exercise and perform mental tests differently than they would under more typical conditions. A young child, for example, who is asked to wear a heart-rate monitor while exercising in a controlled laboratory environment, may respond quite differently to the exercise intervention than if asked to exercise as part of a routine physical education class.

(c) *Pre-testing* Tests administered to participants may influence their sensitivity or responsiveness to the intervention. Thus, the gains obtained from an exercise intervention conducted under laboratory conditions may not be the same if the intervention were introduced to the general population without pre-testing. For example, an exercise intervention developed for children, tested under laboratory conditions and shown to improve cognitive function, may not have the

same effect on children's mental function when the intervention is introduced to children as a school activity.

(d) *Multiple-treatment interference* It is not uncommon for exercise physiologists to develop participant 'pools' from which to draw individuals for experiments. This practice is particularly useful when individuals are selected for a specified level of physical fitness. Often, one individual will participate in several different studies. This practice, however, jeopardizes the external validity of research conducted to assess psychological variables. An individual's experiences in one research study will carry over to later studies. The cumulative effect of multiple research experiences reduces the degree to which the obtained results can be generalized to other individuals.

Reducing threats to validity

Conducting research that yields useful information concerning a causal relation between an independent variable and dependent variables is clearly difficult to perform. There are many factors that can cloud the exercise-cognition relation. The research design selected for a study plays an important role in dealing with threats to its internal validity. Contemporary researchers have a wide variety of research protocols available to them. However, regardless of the protocol, research designs fall into one of three categories: (1) nonexperimental designs are characterized by the absence of a control condition and data are limited to those collected following an intervention; (2) quasi-experimental designs are characterized by the use of separate groups of participants who are administered tests prior to and following an intervention or set of control conditions. In this design category, participants are not assigned randomly to groups, which results in nonequivalence; (3) the randomized experiment is characterized by a requirement that every participant has an equal opportunity to be assigned to experimental or control conditions. This design is considered the 'gold standard' for researchers. The number of threats to internal validity is greatest in nonexperimental designs and fewest in randomized experiments. Note, however, that while randomized controlled experiments are highly desired, there are situations in which this design is not feasible and data must be acquired using quasi-experimental and nonexperimental approaches.

Summary

Establishing a causal relationship between exercise and cognition appears, on the surface, to be a relatively straightforward process. There are, however, a number of factors that can cloud a researcher's evaluation of the two variables. Research scientists should design studies that limit, as much as possible, threats to the internal and external validity of their studies. Further, an investigator's interpretation of usefulness of published research should be guided by the methodological rigour of the study.

4.3 Task selection issues

A brief history: psychometrics, cognitive psychology and neuropsychology

In the beginning of the twentieth century, Alfred Binet (1857–1911) and his colleague, Theodore Simon (1873–1961), were contracted by the French government to develop an objective test that could measure the mental abilities of children in order to make predictions of 'educability' (Hergenhahn, 1992). Binet's work, along with the development of statistical techniques that measure the strength of the relation between and among variables, ushered in the field of *psychometrics* and the academic study of intelligence. Much of the work performed in this discipline has been conducted by educational psychologists who have, over the past century, developed a multitude of tests to measure a wide variety of mental constructs (Weiner and Stewart, 1984). Today, standardized tests are routinely employed to evaluate students, profile personnel for employers, and to screen recruits for the military. These tests are typically composed of a number of tasks purported to require specific types of mental operations. An individual's performances on various tests are aggregated and a single score that provides an index of general mental ability is calculated.

At approximately the same point in history, laboratory-based experimental research was initiated to examine the components of the mind. The pioneering work conducted by Francis Donders (1818–1889) employed simple and choice reaction time measures to fractionate the components of mental processing and to isolate specific mental processes. The field of *cognitive psychology*', which emerged in the late 1960s, followed the component-process approach to studying mental operations (see Sternberg, 1969a, 1975). Over the past four decades, the primary thrust of many contemporary laboratory researchers has been to develop tasks that measure specific components of processing. Figure 4.2 provides an example of a typical information-processing model (see Sanders, 1998, for a more detailed processing model). In the stimulus-organism-response conceptualization of the mind, environmental stimuli first impact the individual via specialized sensory systems. The information selected from the environment is then operated on in a series of stages, which ultimately provide the basis for responding. Much of the theoretical work performed by contemporary experimental psychologists focuses on specific components of processing.

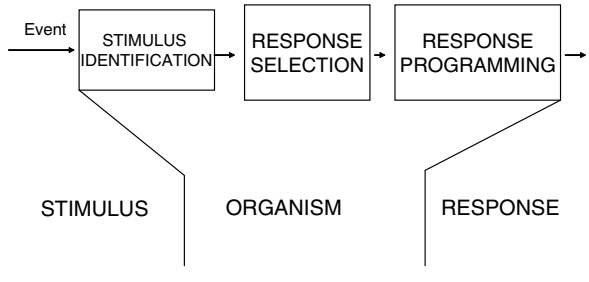

Figure 4.2 A prototypical information-processing model.

Laboratory researchers have, for the most part, focused their research and theory on the test performance of healthy, usually college-aged, individuals. In the first part of the twentieth century there arose a need for specialists who could diagnose and provide treatment for soldiers returning from World War I. Clinical *neuropsychology* emerged as an applied science that focused on brain dysfunction. Demands for psychologists trained in skills required to evaluate, diagnose and treat brain-injured personnel increased with the onset of World War II and other conflicts. Neuropsychologists initially borrowed heavily from the measurement tools developed by educational psychometrists; however, over time, specialized neurological tests were developed to assess specific types of brain damage. In the later half of the twentieth century, methods of measuring brain functions and providing treatment became increasingly more sophisticated. In addition, some experimental psychologists became interested in evaluating theories of cognitive function by evaluating individuals with specific localized brain lesions and with neurological diseases.

The history of psychology is far more complex than the brief overview provided here. The main point to be made, however, is that contemporary researchers often select tests to assess the effects of exercise on cognition without being aware of the origin of the task, the particular context in which the test was developed or, importantly, how test performance is interpreted. The forward-digit span test, for example, which is found in many psychometric tests, is considered a test of attention by clinical neuropsychologists (Lezak, Howieson and Loring, 2004, p 350–351) and a test of memory by cognitive psychologists (Glanzer, 1982). Thus, the interpretation of the meaning of an individual's forward-digit span test performance may depend on the context of the test situation (e.g. clinical versus laboratory) and on the theoretical bias of the researcher. Exercise psychologists who have not received explicit training in psychometrics, cognitive psychology or clinical neuropsychology are faced with the challenge of teasing out differences in the approaches taken by researchers in these areas of specialization. On the other hand, researchers who have undergone specialized training within one of these three disciplines and who are drawn to the study of the relation between exercise and cognition are faced with the fact that there exist alternative methods of measuring psychological phenomena. Reflecting back to topics discussed in the first section of this chapter, science is a self-correcting system that depends on carefully selected and operationally defined constructs. Progress in the field of exercise psychology will depend on continual evaluation of constructs associated with measurement procedures (i.e. tests) and the degree to which they communicate information within the academic community.

Psychological constructs and psychological tests

It is one thing to hypothesize the existence of a psychological construct (e.g. short-term memory) and quite another thing to create a test that accurately measures the construct. Scientists develop abstract concepts that are used to explain causal relations between natural events. Psychological tests are designed to link this abstraction to a set of procedures that are used to measure real-world events. The

method of operationalization, as described previously, is used by scientists to evaluate an abstract construct in an objective fashion. The usefulness of a psychological test is determined by its *construct validity*; that is, the extent to which the test actually mirrors the psychological construct under investigation. For example, one can find 'psychological tests' published in lay magazines designed for the general public; however, while these tests may provide a measurement outcome, how much faith should one place in the interpretations provided? Numerous texts are available that address topics concerned with construct validity. Common to these presentations are several methods used to determine construct validity, these include: *face validity*, which is reflected in the extent to which a test seems likely to provide measures of the construct of interest; *content validity*, which provides an estimate of the degree to which items or characteristics of a test correspond to the construct being evaluated; *predictive validity*, which is established when the measures obtained from a test are able to predict future outcomes that it should, based on theory, be able to predict; *concurrent validity*, which is demonstrated when scores obtained on a test differ between groups of individuals who would be predicted to perform differently. *Convergent validity and discriminant validity* provide an estimate of the degree to which measures are similar to those of other tests that measure the construct and differ from those of the tests that measure other constructs.

The psychological tests developed by researchers in the three disciplines described above differ in the extent to which tests are evaluated in terms of content validity. Traditionally, researchers in the psychometric domain placed considerable emphasis on verifying the construct validity of tests that were developed. Historically, less emphasis has been placed on determining the content validity of tests developed by neuropsychological researchers and even less by experimental-cognitive researchers. It has been recognized for some time that many of the laboratory tests commonly used to assess cognitive processes, in general, and executive functions, in particular, have low test/re-test reliability and uncertain validity (Denckla, 1996; Hughes and Graham, 2002; Rabbitt, 1997). As such, researchers who focus on exercise-cognition relations should be sensitive to the construct validity of the psychological tests selected for their studies.

An inventory of psychological tests

Researchers in each of the disciplines of psychometrics, cognitive psychology and neuropsychology have developed tests designed to assess specific types of mental processing. The voluminous work conducted by Muriel Lezak and her colleagues (Lezak, Howieson and Loring, 2004) provides an excellent description of many neuropsychological tests that have been developed. Many of these tests have been selected to assess the effects of exercise on cognition. The mental processes evaluated in the extant research are outlined below.

(a) *Perception* Humans have evolved intricate biological systems to sense the environment. Sensation refers to the detection of physical energy that influences

sensory receptors, while perception involves the interpretation of sensory events. Classical psychophysical research focused on the interface or interplay between the physical world and the mental world. Tests designed to assess stimulus-detection thresholds have been shown to be affected by acute bouts of physical activity (e.g. critical flicker fusion test). Cognitive psychologists have developed perceptual span tasks that provide indices of iconic (visual) storage and echoic (auditory) storage. It is unknown if acute exercise affects these processes.

(b) *Pattern recognition* An important facet of human cognition is the capacity to organize the input of a large amount of perceptual information into conceptual information. The capacity to recognize familiar patterns provides the basis for identifying or classifying what is experienced. Cognitive psychologists have demonstrated repeatedly that an individual's expectancies can influence how incoming environmental information is 'worked on' and organized. Priming techniques involve the presentation of pairs of stimuli. Information inherent in the first stimulus influences how the individual will respond to the second stimulus. Depending on the type of information presented in the first stimulus, an individual's response speed to the second stimulus can be either facilitated or impaired. Priming tasks are robust and have been employed extensively to determine how individuals extract information from a complex and ever-changing world. Exercise psychologists have evaluated the impact of both acute bouts of physical activity and chronic exercise training on participants' pattern-recognition abilities.

(c) *Attention* Humans demonstrate the capacity to concentrate on one thought or action, to select one environmental object and to disregard others, and to maintain concentration and mental effort over long periods of time. These behaviours provide the basis for the constructs of focused attention, selective attention and sustained attention (or vigilance). The ubiquitous nature of attention has led to extensive theorizing and research. Cognitive psychologists have developed a number of tasks designed to assess specific types of attentional processing. Likewise, neuropsychologists have developed specific tests to assess the effects of injury or disease on the brain. Exercise psychologists have incorporated many of these tests into studies that have examined the impact of acute bouts of physical activity and chronic exercise training on cognitive performance. The study of exercise's effects on attentional processes has been an extremely fruitful area of investigation, with numerous studies demonstrating exercise-related alterations in attentional processes.

(d) *Memory* Memories are past experiences which can be recalled. The processes of memory include learning, retention, recall and recognition. The experimental study of memory can be traced historically to the methods developed by Hermann Ebbinghaus (1850–1909). The tasks he developed and those created by experimental psychologists during the early twentieth century led to the

conceptualization of two types of memory stores – short-term and long-term memory. The dual-mode conceptualization of memory has been vigorously debated by cognitive psychologists for decades (Solso, 1995). Considerable empirical evidence drawn from neuropsychology provides compelling support for the existence of two memory systems, however. The effects of exercise on learning and memory have been investigated in several experiments. While there are exceptions (Pereira *et al.*, 2007; Potter and Keeling, 2005), the results of most of studies conducted with humans do not provide strong support for a relation between acute bouts of exercise or chronic exercise on either short-term or long-term memory processes.

(e) *Working memory* Theoretical debate concerning the nature of memory led some researchers to focus on specific aspects of memory processes (Anderson, 1983; Baddeley, 1986). The construct of 'working memory' evolved from theorizing about the functions of short-term memory. Working memory refers to the temporary storage and manipulation of information necessary for complex tasks such as learning, language comprehension and reasoning. Subjectively, working memory is analogous to conscious awareness and involves the simultaneous storage and processing of information (Miyake and Shah, 1999a). The constraints of working memory are known to limit human performance and, as such, it has been a focus of interest for a number of exercise psychologists. Numerous tests of working memory have been developed by cognitive psychologists and clinical neuropsychologists. Evidence for a relationship between exercise and working memory is relatively strong, with several studies reporting improved performance, particularly on such tasks as the paced auditory serial addition tests.

(f) *Executive function* Mental processes that are central to decision-making, goal planning and choice behaviour are referred to as 'executive' functions (Miyake *et al.*, 2000; Naglieri and Johnson, 2000; Posner and Dahaene, 1994). The construct of executive function has been a focus of interest to cognitive psychologists for decades (Monsell and Driver, 2000; Vandierendonck, 2000). While debate concerning the structure of executive function is ongoing, there is a general consensus among researchers that executive function is not a unitary process; rather, it reflects a number of more elemental, underlying processes. Purported component processes include: planning, which reflects the ability to utilize strategies to attain goals; updating, which is closely linked to working memory and the need to monitor its representation; inhibition, which involves the deliberate suppression of a pre-potent response; and switching, which requires individuals to disengage the processing operations of an irrelevant task and to engage operations involved in a relevant task. Many of these processes have also been classified as metacognition, which refers to higher-order thinking that controls thought processes required for problem solving (Borkowski, Carr and Pressely, 1987; Flavell, 1979). Numerous methods have been developed by cognitive psychologists and by clinical neuropsychologists

to assess executive function (Royall *et al.*, 2002). A considerable number of studies have been conducted to assess the effects of both acute bouts of physical activity and chronic exercise training on executive function. Tests designed to assess executive function figure prominently in research conducted with children (see Chapter 13), older adults (see Chapter 12) and individuals with developmental disabilities (see Chapter 14).

(g) *Concept formation and reasoning* Cognitive scientists are interested in how humans use strategies and goal-oriented plans to solve complex problems. In general, problem-solving tasks fall into two categories: well-defined and ill-defined problems. Well-defined problems are characterized by having an initial condition, a goal condition and path constraints. Ill-defined problems are characterized by the lack of a definite starting point and the lack of a clearly stated goal (Newell, 1980; Newell and Simon, 1972). Often problems are used on the basis of analogies; that is, contrasting the characteristics of a current problem with previous problems. A number of tests designed to measure reasoning abilities were developed as components of general tests of intelligence (e.g. Wechsler adult intelligence scale; Stanford–Binet IQ test). Relatively few published studies have examined the effects of exercise training these mental processes (see Chapter 13).

(h) *Test Batteries* Several commercially available psychological test batteries have been developed over the past decade. These computer based test batteries typically include tasks designed for use in laboratory studies of cognition and tasks developed by neuropsychologists. Examples of the test batteries include the Cambridge neuropsychological test automated battery (CANTAB), HeadMinder and ImPACT. The CANTAB has been used extensively in psychopharmacology and neuropsychological research, while the HeadMinder and ImPACT are often used by practitioners in the fields of physical rehabilitation and athletic training. There are several advantages to using these test batteries. The tests are designed to be easy to administer, the psychometric properties of the tests that comprise the battery have undergone considerable evaluation and normative data are available. There are, however, limitations. The systems are somewhat expensive, the reliability of some tests has been a concern and the validity of using the test batteries, particularly with children and older adults, is yet to be fully determined (Lowe and Rabbitt, 1998; Luciana, 2003). These test batteries have seldom been used by researchers interested in the exercise-cognition relation.

Summary

Psychometricians, cognitive psychologists and clinical neuropsychologists have developed an assortment of mental tasks that assess a wide range of cognitive functions. Researchers are urged to view these tasks as tools that can be used to test predictions derived from scientific inquiry (i.e. inductive and deductive reasoning). Too often,

however, researchers appear to select a test more for its popularity than for the information it may provide concerning mental processes. Tests selected for research should evidence appropriate levels of test-retest reliability and stability (see Baumgartner *et al.*, 2007). Many of the tests of the psychological construct of executive function, which has become the *sine qua non* for many contemporary exercise researchers, are known to suffer from low reliability (Rabbitt, 1997). To address this concern, some have recommended the use of a latent-variable approach in which the commonality of participants' performance on several theoretically related tasks is evaluated (Miyake *et al.*, 2000). The test's sensitivity to change should also be considered. A fundamental requirement of an interpretable dependent measure is that the measure adequately reflects changes that are brought about by the manipulation of an independent variable (Lipsey, 1990). Scaling procedures can influence the capacity of a test to demonstrate the influence of an independent variable.

4.4 Conclusions and recommendations

Reviews of research conducted prior to 1985 reveal a piecemeal approach toward test selection and the use of weak study designs (Tomporowski and Ellis, 1986). The methodological rigour of studies conducted over the past two decades has increased greatly and there is now substantial evidence for a causal relationship between exercise and cognition. Advances have been made because research has become increasingly more theory driven than in the past. Several research groups have assessed the effects of acute bouts of exercise based on predictions generated by arousal and energetics theory (see McMorris and Graydon, 2000; Sanders, 1983; Van der Molen, 1996). Other groups of researchers have examined the effects of chronic exercise training based on contemporary hypotheses concerning executive function (Colcombe and Kramer, 2003). It is no longer a matter of asking the question, 'Does exercise influence cognition?' That question has been answered in the affirmative.

Advances in understanding the phenomenon will depend on addressing specific research questions. Successfully answering these questions will depend greatly on the methodological integrity of the research conducted. Given the topics addressed in the present chapter, several recommendations concerning the task selection are in order.

(1) Researchers are urged to continue to develop studies driven by hypotheses derived from general theories of cognitive function. These studies should be designed to clarify the relation between exercise and cognition. That being said, researchers should be aware that many contemporary cognitive theories are in a constant state of flux and are modified based on the accumulation of empirical facts. Thus, exercise researchers are urged to keep abreast of changes and be responsive to new developments within academic cognitive psychology.

(2) Researchers should include in their studies precise descriptions of exercise manipulations and the physiological responses they elicit.

(3) Researchers should provide information concerning the reliability and stability of the outcome measures used in their studies.

(4) Results obtained from studies that evaluate the exercise-cognition relationship should be interpreted in light of the strength of the study design and threats to internal and external validity.

PART 2

ACUTE EXERCISE AND COGNITION

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Exercise, dehydration and cognitive function

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Even during exercise the human body attempts to maintain homeostasis. Part of this state of homeostasis is temperature regulation. Physical activity utilizes energy, which is turned into heat and so the person's temperature rises. Receptors in the anterior hypothalamus detect increases in temperature and initiate sweating. While sweating is very necessary, and basically good for us, it also includes the loss of fluids, which can be very bad. A large loss of fluid leads to dehydration (also known as hypohydration). Dehydration, resulting from a variety of causes, has been shown to have negative effects on cognition (e.g. Choma, Sforzo and Keller, 1998; Riegel *et al.*, 2002). Thus, one would assume that exercise-induced dehydration would also negatively affect cognitive function. However, there may be an interaction between the positive effects of exercise and the negative effects of dehydration. Despite this, little research has examined the effect of exercise-induced dehydration on cognitive performance. This is very surprising given the fact that sports people and the military often work in conditions that increase the likelihood of dehydration.

Changes in body fluid are detected by osmoreceptors, which are situated in the hypothalamus. Osmoreceptors induce the synthesis of antidiuretic hormone (ADH), which is also known as arginine vasopressin (AVP) or simply vasopressin. ADH is synthesized by cells in the supraoptic and paraventricular nuclei of the hypothalamus and transported to the neurohypophysius (or posterior pituitary) from where it is released into the blood. We should note that ADH is also secreted as the result of other endocrinological activity and physiological responses, in particular the volume and pressure of the vascular system.

The synthesis of ADH as a result of dehydration is important with regard to the exercise-cognitive function interaction because of its potential role in hypothalamic-pituitary-adrenal (HPA) axis activity. As we saw in Chapter 2, one of the main roles of the HPA axis is to regulate the synthesis of corticotropin releasing hormone (CRH),

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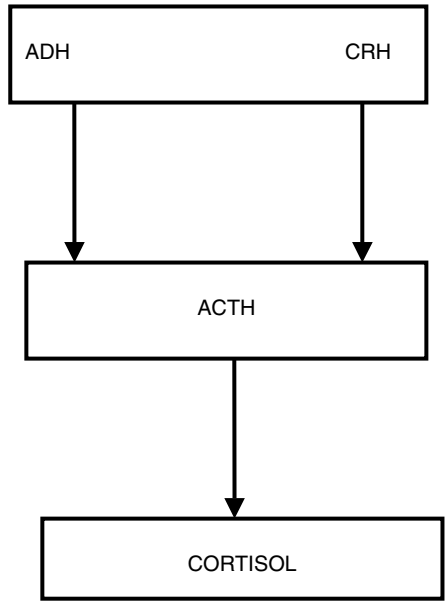

Figure 5.1 Anti-diuretic hormone (ADH) and corticotrophin-releasing hormone (CRH) stimulate the secretion of adrenocorticotropin hormone (ACTH), which in turn stimulates the release of cortisol.

adrenocorticotropin hormone (ACTH) and cortisol. CRH is synthesized in the paraventricular neurons of the hypothalamus, the same region in which ADH synthesis takes place. Both are stored in hypophyseal vessels in the median eminence. During stress, ADH augments CRH activity in the synthesis of ACTH, which in turn stimulates the production of cortisol (see Figure 5.1). For a fuller description of this process see Chapter 2.

Cortisol is important because it regulates the synthesis of ADH and ACTH. However, when the person is in a dehydrated state this inhibiting effect is impaired. Dehydration results in increased concentrations of ADH in the median eminence resulting in oversecretion of ADH into pituitary portal circulation. This, in turn, stimulates oversecretion of ACTH, with cortisol being unable to regulate matters even when cortisol concentrations are very high. The effects of this on cognition are discussed below.

We should note here that dehydration also results in increases in plasma concentrations of the catecholamines adrenaline and noradrenaline. Noradrenaline, in particular, appears to be affected by dehydration. When the individual is in a dehydrated state, increases in core temperature result in vasodilation in the periphery. In order to compensate for this, vasoconstriction takes place in other vascular beds. Noradrenaline is the main neurotransmitter involved in this process (Melin *et al.*, 1997). Increases in adrenaline are probably due to the need to regulate the cardiovascular system, although it has been claimed that it is the result of increased feelings of physical discomfort (Kjaer, 1989). Noradrenaline and adrenaline are

synthesized and secreted by the sympathoadrenal system (SAS). As we saw in Chapter 2, SAS activity results in feedback from the muscles and cardiovascular system to the hypothalamus via the autonomic nervous system (ANS) stimulating the release of the neurotransmitters noradrenaline and dopamine in the brain. These neurotransmitters play large roles in both cognition and emotions. We should also note that ADH itself acts as a neurotransmitter in the brain, in particular in the hippocampus where it plays a role in memory consolidation (Hopper *et al.*, 2004).

5.1 Exercise-induced dehydration and cognitive function

In Chapter 2, we saw how activity of the SAS and HPA axis during exercise are thought to affect cognitive function. Increases in plasma concentrations of cortisol appear to be good indicators of increased arousal (Hodgson *et al.*, 2008). Thus, at first glance, we might expect exercise-induced dehydration to also exhibit an inverted-U effect on cognition. This, however, fails to take into account the nature of exercise-induced dehydration. Even when exercise takes place in heat, dehydration does not occur until the individual cannot maintain a state of homeostasis (Shirreffs, 2000). Thus, dehydration is probably indicative of high levels of arousal.

Stress induced by dehydration may differ from that resulting from exercise per se or indeed most other stressors. Selye (1956) believed that stress could be both good and bad aned took the inverted-U relationship between stress and performance of a variety of tasks for granted. Selye died before CRH was discovered but he had long claimed that a hormone that triggered cortisol synthesis existed. I doubt that he would have been surprised to find that another hormone ADH could also initiate the synthesis of cortisol. The difference in the synthesis of ACTH and cortisol as a result of CRH activity and ADH activity, however, is in the intensity of the stress required. CRH will initiate ACTH and cortisol production when stress is relatively low as well as high. ADH only has an effect when stress is high (Genuth, 2004).

Research

When examining the research into the effect of exercise-induced dehydration on cognitive function, we will take a chronological approach. We will see, however, that most of the researchers included a heat element which may have affected results. This is examined in the final part of the chapter. The first to examine the effect of dehydration on cognitive function were Sharma *et al.* (1986). Like several of those who were to follow them, these authors divided their experiment into two stages. In the first stage, they attempted to examine the effect of heat-induced dehydration on cognition and in the second stage they included exercise as well as heat.

The design and procedure used by Sharma *et al.* (1986) were quite complicated. In many ways they may appear to be overcomplicated but the authors were keen to ensure that their independent variable, dehydration, was not affected by intervening variables, such as emotional responses to heat. Immediately prior to the experiment,

subjects ($N = 8$), who had been heat-acclimatized, drank water 'to the extent of 1% of their body-weight' (p. 792) and then rested for a period of 1 hour in a thermoneutral room ($27 \pm 1\,^{\circ}C$, relative humidity 50%). Following this, subjects emptied their bladders and entered an environmental chamber. There were two heat conditions, a dry condition and a humid condition. In the dry condition temperature was set at $45\,^{\circ}C$, with relative humidity 35%, and in the humid condition the temperature was $39\,^{\circ}C$, with a relative humidity of 60%. Subjects undertook what the authors described as 'moderate work (15 steps min^{-1} on a 38 cm stool)' (p. 792). No information is given with regard to heart rate or any other physiological measure which would allow us to assess the true intensity of this exercise. During this period subjects were continually weighed and continued exercising until they had reached one of three percentages of body mass loss, 1%, 2% or 3%. Subjects also carried out a control test in an euhydrated state with no loss of body mass. Thus, there were seven conditions – control, dry with body mass loss of 1%, dry with body mass loss of 2%, dry with body mass loss of 3%, humid with body mass loss of 1%, humid with body mass loss of 2% and humid with body mass loss of 3%.

Once the target body mass loss had been achieved subjects returned to the thermoneutral room where they stayed for 90 mins. In this time they were not allowed any fluids. By moving from the hot environmental chamber to a thermoneutral room, negative effects of heat, other than dehydration, would be eliminated. Following this rest period, they undertook three cognitive tests which they termed a substitution test, a concentration test and a psychomotor test. In the substitution test subjects were given a series of English letters. Opposite each letter there was an uncommon geometric shape. After initial exposure, the authors do not state how long the subjects had to memorize the pairs, they were given a row of shapes and, in 3 mins, had to write the correct letter below each shape. In the concentration test, ten series of numbers were read out to the subjects at a rate of one number per second. At unpredictable intervals the experimenter instructed the subjects to recall the last five digits read out but in reverse order. In the psychomotor test, subjects had to move a stylus round a star shape, which had a 0.5 cm groove around it. They had to keep the stylus within the groove.

After completing the cognitive tests subjects were re-weighed and then exercised on a cycle ergometer at 4 W for 40 mins. Individual fitness levels were not taken into account. This could undoubtedly have affected results. Following completion of the exercise, subjects carried out the cognitive tests again. The authors termed this the 'superimposed heat stress and exercise' (p. 795) condition. Mean heart rates at each percentage of body mass loss differed, but only by a small amount. Rates ranged from 122 to 149 bpm for the dry conditions and from 118 to143 bpm for the humid. No standard deviations are supplied. Given the mean ages of the subjects this would amount to between ~62 and ~76% estimated maximum heart rate in the dry conditions and ~61 to ~73% estimated maximum heart rate in the humid conditions.

Results for the first set of cognitive tests, that is those following the 90 mins rest in the thermoneutral room, showed no significant effect of dehydration on performance in the substitution test, although there was a definite trend for a decrease in

performance from the control condition to 3% body mass loss. Given the small sample size, a Type II error is possible. For the concentration test, there was a significant main effect for dehydration levels, with a decrease in performance at the 2 and 3% body mass loss conditions. Similar results were shown for the psychomotor test.

The way in which the results for the superimposed heat stress and exercise condition are reported would not be allowed today. The authors state that they used a 2×4 (dry/humid $\times$ % body mass loss) analysis of variance and report the hot dry and humid conditions separately, therefore we must conclude that an interaction effect was shown, although this is never stated. In the dry condition, there was no significant effect on the substitution test, although a linear trend was again demonstrated with scores deteriorating with increased dehydration. Results for the concentration test showed significant decreases following 2% dehydration, while the psychomotor tests demonstrated a linear decrease from 1% onwards. Results for the humid condition were similar, with no significant effect on substitution, a linear decrement from 1% for the concentration test and a decrease in performance from 2% on for the psychomotor test. From these data the authors argued that 2% loss of body mass was a significant threshold level for dehydration to demonstrate a significant effect on cognitive performance. Given the overall significant results, the small sample size and the trends at the 1% level, I think that this is somewhat dubious. I do not see how these data preclude a linear decrement from 1% onwards. They certainly provide a prima facie case for such an effect.

Gopinathan, Pichan and Sharma (1988) carried out a similar experiment. Subjects ($N = 11$) began by emptying their bladders and resting in a thermoneutral room (temperature $25 \pm 1^{\circ}$ C, relative humidity is not given) for 1 hour, 'to compensate for any residual dehydration' (p. 16). Subjects then entered an environmental chamber (temperature 45 °C, relative humidity 30%). They undertook continuous work (15 steps min^{-1} on a 38 cm high stool). Subjects' weights were continually monitored and they remained in the chamber and continued working until they reached one of four dehydrated states, 1%, 2%, 3% and 4% loss of body mass. On achieving the desired weight loss, the subject was removed from the chamber and rested in a thermoneutral room until pre-exercise heart rate and oral temperature had been reached. Thus, the length of time of this stage would vary from person to person. The authors claimed that this was to overcome the effects, other than dehydration, of exercise and heat stress. With regard to the latter, core temperature would have been a much better measure than oral temperature. Cognitive testing took place pre-exercise and post-recovery.

The cognitive tests were a word recognition test, serial addition and trail-making. In the word recognition test, the experimenter read out a list of 52 words, one word every 2 s. Immediately after completion of the reading, the subject was provided with a list of 15 words and had to state which had been heard previously. The serial addition test required subjects to mentally add series of five numbers. The trail-making test required the subject to join up a series of letters and numbers in the correct order. Both letters and numbers were 'scattered' around a sheet of paper. Subjects had to

alternate between joining two numbers then two letters. The speed of completion was the dependent variable.

Performance on the word recognition task showed a significant linear decrease in performance from 2% onwards. The addition test demonstrated a significant drop in performance at 2% followed by another drop at 4%. The trail-making test showed a significant linear decrease in speed from 1% onwards. Despite this latter finding the authors claimed that 2% dehydration was the threshold for a decrement in performance to be seen. However, observation of the word recognition and addition data at 1% compared to euhydration suggests the possibility of a Type II error. This is discussed in the final section of this chapter.

Of greater interest to us is the research of Cian and associates (Cian *et al.*, 2000, 2001). Cian *et al.* (2000) compared the effect of heat-induced and exercise-induced dehydration on cognition. Their subjects ($N = 8$) began by resting in a thermoneutral room (25 °C, relative humidity 40%) for 90 mins. They then undertook a series of psychological tests. After completing the tests, subjects were dehydrated either by heat or exercise, hyperhydrated by glycerol ingestion or euhydration was maintained.

In the euhydration and hyperhydration conditions subjects remained sitting in the thermoneutral room for 2 hours. Euhydration was maintained by water ingestion. Hyperhydration was achieved by the subject drinking 'a solution containing a quantity equal to 1.1 g kg^{-1} of body weight' (p. 30) of a glycerol flavoured drink and a sodium chloride (NaCl) solution. In the heat dehydration condition, the subject remained in an environmental chamber for 2 hours. A body mass loss of 2.8% was obtained. The authors provide no details of temperature or relative humidity. In the exercise-induced dehydration condition, subjects exercised on a treadmill at 60% of their maximum volume of oxygen uptake (VO_{2MAX}) for ~2 hours and a body mass loss of 2.8% was obtained. After achieving the required hydration state, subjects lay in a semi-recumbent state for 90 mins in the thermoneutral room. The authors report that the second set of psychological tests was carried out 30 mins later. However, I think that this is an error. They provide no information as to what occurred in these 30 mins and in the second experiment (Cian *et al.*, 2001) they stated that testing took place during the last 30 mins of the rest period. This is what I think happened here. I presume that the 90 mins rest period was there to ensure that the only effect on performance of the cognitive tasks was dehydration. In other words, like Sharma *et al.* (1986), they ensured that any negative effects of heat exposure, other than dehydration, were eliminated. Also, the potential positive or negative effects of exercise would be removed.

The second set of cognitive tests was followed by the subjects working an arm-crank ergometer at 80% VO_{2MAX} until they could no longer maintain the required output. This lasted between 15 and 20 mins. Following a 15 min rest period, the psychological tests were re-taken. I presume that this delay was again to ensure that the independent variable was not affected by confounding variables. Thus, cognitive testing took place pre-experiment, post-dehydration and post-arm-cranking. Heart rate measures found that both dehydration states resulted in higher heart rates compared to the euhydrated and hyperhydrated conditions. There were no differences

post-arm-cranking. This may well have been because the arm-cranking was to exhaustion. Thus the physiological stress would be the same for all conditions.

The cognitive tests were a long-term memory visual recall and recognition task, four-choice visual reaction time, perceptual discrimination test (judging the length of a line compared to a criterion line shown 1 s earlier), short-term memory (recall of digits presented for 0.5 and 1 s) and manual tracking. There was no significant post-dehydration effect on reaction time. Performance on the tracking task, in the dehydrated states, was significantly poorer than in the euhydrated state. Similarly, in the perceptual discrimination task performance in both dehydrated states was significantly lower than in the euhydrated state but only for speed of response and not for accuracy. Short-term recall was significantly poorer in the dehydrated states compared to the euhydrated. The authors did not carry out any post hoc tests to examine the difference between hyperhydration and dehydration. Long-term memory was not affected. It should be noted that post hoc tests were by student t-test without a correction factor.

In the post-arm-cranking condition, there were no significant effects on the perceptual comparison and short-term memory tasks. The reaction time task showed a significant improvement in performance in the dehydrated states compared to euhydration. Tracking performance was poorer in the two dehydrated states compared to that in the euhydrated state. In the long-term memory test heat-induced dehydration resulted in poorer performance than exercise-induced dehydration and euhydration. The authors concluded that dehydration was the key to inducing inhibition of performance regardless of whether it was heat or exercise induced.

In the second Cian *et al.* (2001) experiment, seven subjects undertook cognitive tests following five conditions: heat exposure with fluid ingestion; heat exposure without fluid; exercise with fluid ingestion; exercise without fluid; and a control situation. Pre-experiment the subject remained in a thermoneutral room (25 °C, relative humidity 40%) for 1 hour. In the control condition, the subject remained in the room for a further 2 hours. In the heat conditions subjects were dehydrated to obtain a 2.8% body mass loss in an environmental chamber. Temperature and relative humidity were manipulated to ensure a constant core temperature of 38 ° C. In the exercise conditions subjects exercised on a cycle ergometer at 65% VO_{2MAX} for ~2 hours and a body mass loss of 2.8% was obtained. Room temperature was controlled to ensure a core temperature of 39 °C. Although there was only a 1 °C difference in core temperature between the heat and exercise conditions this could be important with regard to core temperature. In the control condition, water was drunk to ensure euhydration but in the other conditions no fluid was taken. Following this, subjects returned to the thermoneutral room for 1 hour. Cognitive tests were undertaken 30 mins into this period (Test 1). After 1 hour, the subject drank a glucose solution taken in two parts, 30 mins apart. The nature of this solution depended on the condition. In the heat with fluid and exercise with fluid conditions, subjects drank a solution containing 50 g l^{-1} glucose, 1.34 g l^{-1} NaCl and 1.5 ml l^{-1} water with sugar-free green lemon flavouring. The amount corresponded to 100% body mass loss. De facto these were rehydration conditions. In the without fluid

conditions, subjects drank the same quantity of glucose diluted in 100 ml water. Cognitive tests were undertaken 2 hours after the second fluid ingestion (Test 2). The same tests as in the Cian *et al.* (2000) study were undertaken.

Results for reaction time and tracking tests were unaffected by any condition. There were no effects on the perpetual comparison task for accuracy, but for speed of response the control time was significantly shorter than that in the other conditions in both Tests 1 and 2. While we might expect this for the without fluid conditions, one would have expected the rehydrated groups to have recorded times similar to the control group at Test 2. Short-term memory was unaffected. Similarly, there was no affect on long-term memory in Test 1 but in Test 2 both with fluid ingestion conditions induced comparatively better performance than those in the without fluid conditions. These results, overall, do not really provide a great deal of support for the claim that dehydration disrupts cognitive performance.

Grego *et al.* (2005) set out to examine the effect of exercise-induced dehydration on cognitive function without the confounding effect of heat. They had a group of endurance trained cyclists and/or triathletes ($N = 8$) carry out cognitive tasks before, during and after two 3 hour rides on a cycle ergometer at 60% VO_{2MAX} in a controlled environment (temperature 20–21 °C, relative humidity $50 \pm 5\%$), one with fluid ingestion and one without. They also examined a control group over a 3 hour period. This was to ensure that they could be confident that results were due to dehydration per se rather than being affected by boredom or learning. In the fluid ingestion condition, 400 ml of mineral water (Na^+ 0.5 mEq l^{-1}, K^+ 0.17 mEq l^{-1}, HCO_3 1.16 mEq l^{-1}) was taken immediately prior to exercise and 200 ml of the same solution at 20 min intervals throughout the 3 hours. Subjects lost 4.1% body mass in the no fluid intake condition and 2.2% in the fluid condition.

The cognitive tasks were the critical flicker fusion (CFF) test and a map recognition task. CFF is generally thought to be a measure of central nervous system (CNS) activation (Holmberg, 1981; Barbanoj *et al.*, 2006). In the map recognition task, subjects were shown, on a slide projector, a map divided into 12 sectors. Viewing time was 1 min. Following this, they were presented with a series of slides of similar sectors, some of which had been present in the original map and some which had not. The subject had to state, as quickly and accurately as possible, whether the slide had been seen previously or not. There were two dependent variables, speed of recognition and number of errors. Testing took place pre-exercise, in the last 5 mins of each 20 min section, and within 5 mins of completion. Pre- to post-exercise results were compared separately from results for the during exercise conditions. I am not certain that this is acceptable, as the post-exercise results will undoubtedly have been affected by testing during exercise. The dehydration group's cognitive performance did not differ to that of the control group.

Next I will report an experiment (McMorris *et al.*, 2006) carried out in our laboratory. I have some qualms about including it as we were concerned with heat-induced dehydration per se and only used a very light intensity of exercise. However, we also examined plasma concentrations of adrenaline, noradrenaline, 5-hydroxytryptamine (5-HT), also know as serotonin, and cortisol, pre-treatment,

post-treatment and following a recovery period. The results from this analysis provide some interesting data which I will comment on later We examined the cognitive performance of our subjects ($N = 8$) pre-treatment and then following mild exercise in both a temperate (temperature 20 °C, relative humidity 40%) and heat condition (temperature 36 °C, relative humidity 75%). In both conditions, subjects rode on a cycle ergometer at a workload of 100 W for 20 min, followed by a 10 min rest before repeating the 20 mins cycle ride. A pilot study had shown that for these subjects, who were all fit sports science majors, cycling for this length of time at this resistance induced only small increases in heart rate. Moreover, following the second bout of exercise the subject sat in the environmental chamber for 70 min. The aim of the exercise was to help increase body mass loss over the 2 hour period. To further aid this, in the heat condition, subjects wore a polyvinyl chloride suit throughout. Following treatment, the subjects undertook the cognitive tests again followed by a 2 hour recovery period. The recovery consisted of sitting in a thermoneutral room (temperature 24.94 ± 1.28 °C). During recovery in the heat condition, subjects drank 250 ml of 40 mM NaCl solution following completion of the cognitive tests. They then drank every 20 mins over a 2 hour period. The amount drunk every 20 mins was calculated to ensure that over the recovery periods the subjects would have ingested 1 l for every 1 kg of weight loss. Subjects undertook the cognitive tests post-recovery.

The cognitive tests were random movement generation, verbal and spatial short-term memory and four-choice visual reaction time. The random movement generation test was a spatial version of the Baddeley *et al.* (1998) random number generation test. Subjects sat at a display board, holding a stylus. The board contained eight circular brass plates, arranged in a semi-circular pattern, plus one home plate. The subject placed the stylus on the home plate, which was situated in the centre of the board. The subject had to move the stylus from the home plate to any of the other plates and back again on the sound of a ringing tone. The speed of response was set at 1.5 Hz. Subjects were told to respond in a random fashion, that is no patterns should emerge. They were told to avoid patterns such as repeatedly touching adjacent plates, making V-shaped movements or repetitively touching the same series of plates. The test lasted 1 min. The dependent variable was the random movement generation index, a spatial variation of Evans (1978) random number generation index. This test is a central executive task (Baddeley, 1986; Heuer, Kohlisch and Klein, 2005).

There were two verbal short-term memory tasks, forward and backward number recall. In the forward recall test, the experimenter read out a series of numbers and, when the experimenter stopped, the subject had to repeat them immediately. The experimenter began with three numbers and increased the amount by one every trial. The dependent variable was the amount of numbers repeated in the final successful trial. The same procedure was undertaken in the backward recall test except that the subject had to give the answers in reverse order. This is a test of what Baddeley (1986) termed the phonological loop.

There were also two spatial short-term memory tasks, forward and backward recall. These were modified versions of the Corsi block tapping test (Corsi, 1972). Subjects sat facing the display board used in the random movement generation test.

The experimenter pointed to a number of plates in a given order. The subject had to point to the same plates. In the forward condition, the subject repeated the same order as the experimenter and in the backward condition reverse order was used. As with the verbal test, the experimenter began with three plates and increased the amount by one every trial. The dependent variable was the amount of plates repeated in the final successful trial. This is a test of the visuo-spatial sketchpad (Baddeley, 1986). The final test was a classic four-choice visual reaction time test.

Post-treatment, there were significant effects of dehydration on the random movement generation task, however the other tasks were not affected. Post-recovery, none of the variables differed significantly between the dehydration and control conditions. In line with Drevets *et al.* (1995) and Dietrich and Sparling (2004), we claimed that random movement generation was affected because it is a central executive task, activating the prefrontal cortex and also requiring recall from other parts of the brain. On the other hand, the other tasks activate areas of the brain that are less susceptible to stress.

The biochemical data showed that although there were significant increases in adrenaline, noradrenaline, 5-HT and cortisol concentrations in the dehydration condition post-test, the only difference between the dehydration and control conditions was for cortisol concentrations. Rehydration resulted in this difference disappearing. There were significant regression correlations between changes in cortisol from pre- to post-treatment (Δ) and Δ random movement generation ($R^2 = 0.26$, $p < 0.05$). Percent body mass loss also demonstrated a significant regression correlation with Δ random movement generation ($R^2 = 0.34$, $p < 0.05$). Post-recovery, Δ adrenaline concentrations correlated significantly with Δ random movement generation ($R^2 = 0.48$, $p < 0.01$). There were no other significant regression correlations. The post-treatment condition β values showed the expected relationship with higher concentrations and weight loss being indicative of poorer performance on the random movement generation test. However, the β values post-recovery showed that higher adrenaline concentrations were indicative of better performance on the random movement generation test. We argued that in the post-treatment condition greater increases in cortisol concentrations were probably indicative of distress, which would also be related to high levels of arousal and hence poorer performance. The higher post-recovery Δ adrenaline concentrations were probably indicative of moderate increases in arousal and hence better cognitive function. The significance of these findings will be discussed in the final section of this chapter.

Serwah and Marino (2006) examined the effect of cycling at 70% peak power output for 90 mins or until exhaustion, whichever came first, in a warm humid condition (31 °C, relative humidity 63%). Subjects undertook simple, two-choice and four-choice reaction time tests pre-exercise, after 40 mins and on cessation of exercise. There were three hydration conditions. In one, subjects ingested water equivalent to 100% of their fluid loss. In the second, they ingested water equivalent to 50% loss, while, in the third condition, no fluid was taken. They showed no significant effect of dehydration but there was a main effect for exercise, with reaction time at rest being significantly slower than at 40 mins and immediately following exercise.

Tomporowski *et al.* (2007a) had subjects ($N = 11$) carry out cognitive tests during and after exercise in four conditions. Subjects exercised on a cycle ergometer at 60% VO_{2MAX} for 15, 60 or 120 mins without fluid intake and for 120 mins with fluid ingestion. This was immediately followed by a graded exercise test to VO_{2MAX}. In the 120 min ride with fluid ingestion, subjects drank a commercially available 7% carbohydrate electrolyte sport drink every 15 mins. The amount drunk was determined in order to maintain euhydration. Cognitive tests were undertaken pre-exercise and 'within 5 min' (p. 893) of the graded exercise test. Testing took place in an environmental chamber (temperature 30 °C, relative humidity 40%). The cognitive tests were a category switching test, which activates the central executive, and the Brown–Peterson short-term memory test. Performance on the central executive task showed significant differences following exercise with no differences between conditions. However, the results showed a significant decrease in speed but a significant increase in error. Performance on the short-term memory tasks improved significantly following exercise regardless of condition.

At the time of writing, the latest research into the effect of exercise-induced dehydration on cognitive function was by Baker, Conroy and Kenney (2007). They examined basketball players ($N = 11$) in six conditions: euhydration, maintained using a commercially available lemon/lime flavoured carbohydrate electrolyte solution (6% carbohydrate and 18.0 mM NaCl); euhydration, maintained by lemon/lime flavoured water (flavour plus 18.0 mM NaCl); 1% dehydration; 2% dehydration; 3% dehydration; and 4% dehydration. In all conditions subjects exercised in an environmental chamber (temperature 40 °C, relative humidity 20%). The exercise protocol was a series of nine 15 min walks on a treadmill at 50% VO_{2MAX} with 5 mins rest between bouts. In the dehydrated conditions, no fluid was allowed until the subject reached the desired percent body mass loss, after which the subject drank distilled water to maintain the desired percent body mass loss. A cognitive test was undertaken prior to exercising and post-exercise. Following the post-exercise tests the subject sat in a thermoneutral room for 50 mins and the desired hydration state was maintained. Twenty minutes after the rest period, the subject completed a sequence of fast-paced basketball drills. The exercise session was 80 mins in duration and consisted of four 15 min quarters with 5 mins between quarters and 10 mins at half-time. The desired hydration state was maintained using the same protocol as earlier. The cognitive test was re-administered. The cognitive test was an earlier version of the test of variables of attention (TOVA) (Dupuy and Hughes, 2007).

The TOVA is a test of vigilance. Two different stimuli were presented to the subject, one at a time, on a computer screen for 100 ms at 2 s intervals. Both stimuli were white squares but one was identified as the target stimulus. This had a black hole near the top. Subjects had to press a button when the target appeared and to inhibit response when the nontarget appeared. There were two conditions: target-frequent (a target/nontarget ratio of 3.5 : 1) and a target-infrequent (ratio 1 : 3.5). The dependent variables were response speed, errors of omission, errors of commission and sensitivity (ratio of correct responses to errors of commission).

There were no significant differences in performance on the TOVA between the four dehydration states, nor between the two euhydration states, therefore the authors collapsed the dehydration data and euhydration data, producing two conditions. For target-infrequent data, sensitivity showed a significant decrease from pre-exercise to both post-exercise and post-drills. However, neither response time, omission or commission errors differed from baseline, post-exercise, in either condition. Post-drills significantly better performance was demonstrated in the euhydrated state compared to the dehydrated on all variables except commission.

For target frequent data, there were no significant differences from baseline for response time, sensitivity and omissions. In the euhydrated state commissions decreased from baseline at post-exercise only. Post-exercise performance in the euhydrated state was significantly better than in the dehydrated for both omission and commission errors. Post-drills, the euhydrated state elicited greater sensitivity than the dehydrated.

Summary

It is difficult to summarize the research because the designs differed quite considerably. Sharma *et al.* (1986) and Gopinathan, Pichan and Sharma (1988) used very similar methods to induce dehydration but their cognitive tests differed. Even Cian *et al.* (2000, 2001) used different methods in their two experiments. The protocols used by the others (Grego *et al.*, 2005; McMorris *et al.*, 2006; Tomporowski *et al.*, 2007a; Baker, Conroy and Kenney, 2007) all differed markedly both in ways of inducing dehydration and the cognitive tests used. Most authors used heat plus exercise as the method of inducing dehydration, although Grego *et al.* used exercise only. Cian *et al.* (2001) actually compared the effects of exercise-induced, heat-induced and heat plus exercise-induced dehydration on cognition. They decided that the key factor was dehydration rather than the way in which it was obtained.

Gopinathan, Pichan and Sharma (1988) demonstrated significant deteriorations in cognitive performance following dehydration on all three of the cognitive tests they used. However, the other authors found significant decrements in performance on some but not all of the cognitive tests. Possible reasons for this are discussed in the next section of this chapter. Also discussed in the next section is the fact that those authors who examined the effects of different levels of dehydration as determined by differing percentages of body mass loss came to the conclusion that 2% was a threshold that had to be crossed before negative effects would be demonstrated. I believe that examination of the data suggests that this may be a sweeping generalization.

5.2 Discussion

As can be seen from the results described above, findings are not unequivocal. A possible reason for this may be the nature of the cognitive tasks employed as

dependent variables. Several of the tasks can be easily identified as short-term memory tasks, stressing either the phonological loop or visuospatial sketchpad (see Table 5.1). Some of the other tasks, for example choice reaction time, tracking, long-term memory and the vigilance task (TOVA) used by Baker, Conroy and Kenney (2007), are self-explanatory. The CFF test is a psychophysiological examination of the activation of the CNS. Such activation would be related to choice reaction time and performance on the TOVA. The tracking task would also be affected by activation of the CNS although the peripheral nervous system would also be involved. The other tasks are more difficult to classify. One could argue, with a great deal of conviction, that they are all working memory tasks but the amount that they all activate the central executive may be debatable.

There is strong evidence from positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) research to show that random generation tasks and category switching activate the prefrontal cortex and can be accepted as central executive tasks (Spatt and Goldenburg, 1993; Brugger et al., 1996) The addition task of Gopinathan, Pichan and Sharma (1988) would certainly require some input from the phonological loop but should theoretically also require some central executive activity, although the latter may be limited. The perceptual discrimination tasks of Cian *et al.* (2000, 2001)) would require visuospatial sketchpad activation and again

Table 5.1 Classification of tasks.

Authors	Tasks	Classification
Sharma *et al.* (1986)	Substitution	Verbal short-term memory
	Concentration	Verbal short-term memory
	Star tracing	Tracking
Gopinathan, Pichan and Sharma (1988)	Word recognition	Verbal short-term memory
	Addition	Central executive
	Trail-making	Vigilance
Cian *et al.* 2000; 2001)	Visual recall/recognition	Long-term memory
	Choice reaction time	Reaction time
	Perceptual discrimination	Central executive
	Digit recall	Verbal short-term memory
	Manual tracking	Tracking
Grego *et al.* (2005)	Critical flicker fusion	CNS activation
	Map recognition	Visual short-term memory
Serwah and Marino (2006)	Simple reaction time	Reaction time
	Choice reaction time	
McMorris *et al.* (2006)	Random movement generation	Central executive
	Number recall	Verbal short-term memory
	Spatial recall	Visual short-term memory
	Choice reaction time	Reaction time
Tomporowski *et al.* (2007a)	Category switching	Central executive
	Brown–Peterson	Verbal short-term memory

Note: CNS: central nervous system; TOVA: test of variables of attention

some limited central executive activity. Thus, it is difficult to assess the amount to which these two tasks can be classed as central executive tasks. However, we will include them in the classification unless our examination of research results shows that they affected differently to those tasks that we can certainly classify as being central executive tasks. Thus, we have six types of task: central executive; visual short-term memory; verbal short-term memory; vigilance; choice reaction time; long-term memory; CNS activation; and tracking. The next stage is to see if any patterns in results exist. As most of the experimenters examined subjects following a 'dehydration' stage and then had subjects work to exhaustion, which I will call the post-exercise to exhaustion stage, I will examine results for these two conditions separately.

Table 5.2 shows a summary of the findings for each category for post-dehydration conditions. Results for the central executive tasks show that all were negatively

Table 5.2 Summary of post-initial dehydration results for each category.

Category	Result	Author
Central executive	Inhibition	Gopinathan, Pichan and Sharma (1988)
	Inhibition speed: NS accuracy	Cian *et al.* (2000)
	Inhibition speed: NS accuracy	Cian *et al.* (2001)
	Inhibition	McMorris *et al.* (2006)
	Inhibition speed: NS accuracy	Tomporowski *et al.* (2007a)
Verbal short-term memory	Inhibition 1 test: NS 1 test	Sharma *et al.* (1986)
	Inhibition	Gopinathan, Pichan and Sharma (1988)
	Inhibition	Cian *et al.* (2000)
	NS	Cian *et al.* (2001)
	NS	McMorris *et al.* (2006)
	NS	Tomporowski *et al.* (2007a)
Visual short-term memory	NS	Grego *et al.* (2005)
Tracking	Inhibition	Sharma *et al.* (1986)
	Inhibition	Cian *et al.* (2000)
	NS	Cian *et al.* (2001)
Vigilance	Inhibition	Gopinathan, Pichan and Sharma (1988)
		Baker, Conroy and Kenney (2007)
Reaction time	NS	Cian *et al.* (2000)
	NS	Cian *et al.* (2001)
	NS	McMorris *et al.* (2006)
	NS	Serwah and Marino (2006)
CNS activation	NS	Grego *et al.* (2005)
Long-term memory	NS	Cian *et al.* (2000)
	NS	Cian *et al.* (2001)

NB: NS: nonsignificant; CNS: central nervous system

affected by dehydration, although in those that examined speed and accuracy of response (Cian *et al.*, 2000, 2001) only speed was negatively affected. Accuracy was unaffected. The results for speed and those of Gopinathan, Pichan and Sharma (1988) and McMorris *et al.* (2006) are what would be expected with regard to beliefs that prefrontal cortex activity is most likely to be disrupted during stress. The fact that accuracy was unaffected is more difficult to explain. Grego *et al.* (2005) argued that in such circumstances, there might be a change in the speed–accuracy trade-off.

Observation of Table 5.2 suggests that factors other than task type must be affecting the results. Results examining the effect of dehydration on verbal short-term memory are not unequivocal. Tracking tasks show a deterioration, with the exception of the Cian *et al.* (2001) study. To summarize, we can say that the evidence for a negative effect of dehydration on central executive tasks is very strong. There is also fairly strong evidence for a negative effect on tracking tasks and, to a lesser extent, short-term memory and vigilance, while reaction time and long-term memory appear to be unaffected.

Results for the post-exercise to exhaustion conditions are not unequivocal. Dehydration showed no significant effect on central executive tasks (Cian *et al.*, 2000; Tomporowski *et al.*, 2007a). Cian *et al.* (2000) also showed no significant effect on a short-term memory test. This is contradictory to Sharma *et al.* (1986) who found significant deterioration in short-term memory tasks. Both Sharma *et al.* and Cian *et al.* (2000) showed that tracking task performance had deteriorated, while choice reaction time improved. Long-term memory results were surprising, with heat-induced dehydration resulting in a decrement in performance from baseline but exercise-induced dehydration having no significant effect. Vigilance was generally shown to be negatively affected by dehydration (Baker, Conroy and Kenney, 2007). The differences between these results and those post-dehydration are probably best explained by the exercise to exhaustion adding another factor to the stress placed on the individual. This effect may, in some cases, be positive, thus reducing the negative effects of dehydration, while in others it may add to the distress.

Another possible factor affecting results is the differences in heat, relative humidity and body mass loss used in the experiments. There are differences in temperatures, relative humidities and % body mass losses used by each of the authors. As we can see, there are some large differences in temperature and relative humidity, however no obvious effect or trend in results emerges. Indeed, Sharma *et al.* (1986), who compared the effects of exercise in hot/dry and hot/damp conditions, showed only one minor difference in effects. The situation for % body mass loss is less straightforward. Sharma *et al.* (1986) and Gopinathan, Pichan and Sharma (1988) claimed that 2% is a threshold level. However, observation of the data presented in these studies suggests that this may not be the case. There is some evidence of 1% loss inducing deterioration in performance, while > 2% loss has not resulted in deteriorations in performance of all tasks.

Another possible factor is the exercise protocols used in the dehydration phases. Again no obvious trend in results emerges. Although we should note that there are some similarities in exercise length and intensity. In the first stages, that is

inducement of dehydration, length is generally fairly long (60–120 mins), while intensities vary from very low (50% VO_{2MAX}) to moderate (65% VO_{2MAX}). In this stage, no research has examined high intensity exercise.

Several authors (Sharma *et al.*, 1986; Cian *et al.*, 2000; Baker, Conroy and Kenney, 2007) also had subjects exercise to exhaustion post-dehydration and then complete cognitive tests. All showed some negative effects but not on all variables. Thus, it is difficult to say to what extent there is an interaction between the effects of exercise and those of dehydration per se. These results when exercise and dehydration are combined, however, tend to be somewhat different to those found in research where exercise is the only stressor, as we have seen in other chapters in this book. Either dehydration itself is an additional stressor ensuring that arousal levels are high or dehydration only occurs when the stress from exercise is such that the individual is already in a state of distress. These high levels of stress are confirmed by those studies where subjective measures were used (Cian *et al.*, 2001; McMorris *et al.*, 2006). Moreover, the results of these studies show that the subjects were perceiving distress rather than positive arousal. The increases in plasma cortisol concentrations shown by McMorris *et al.* (2006) support this conclusion.

Theoretical issues

The findings of McMorris *et al.* (2006) provide some evidence for the notion that dehydration results in increased concentration of ADH, which in turn leads to increased concentrations of ACTH and cortisol. The resultant levels of distress probably have an effect on brain concentrations of neurotransmitters such as noradrenaline and dopamine, which in turn results in decrements in cognitive function. However, it does not appear that all tasks are affected equally. As with much of the research examined in this book, it does appear that central executive type tasks are the most susceptible to distress, with other working memory tasks also likely to be affected but not necessarily so. These conclusions are supported by the fact that McMorris *et al.* (2006) showed that Δ plasma concentrations of cortisol were a good predictor of Δ performance on the central executive task. An interesting factor with regard to the empirical data is that rehydration appears to result in a return to normal levels of functioning (McMorris *et al.*, 2006). The implications of this are discussed below.

Future research

To me, the most important factor in future research is to ensure that there is a large sample size. Although there is evidence for a higher negative effect of dehydration on central executive tasks than on other types of task, particularly short-term memory and vigilance, it may well be equivocal due to the possibility of Type II errors. While I would not be surprised if comparatively easy tasks, such as choice reaction time, are not affected by dehydration, we still need to eliminate the possibility of Type II errors.

The effect of rehydration also requires exploration. Theoretically one would expect to see the negative effects of dehydration disappear when homeostasis has been restored but the evidence so far is very limited. McMorris *et al.* (2006) showed that rehydration had a positive effect but Sharma *et al.* (1986) found that effects were not unequivocal. We need also to find out whether those who are used to being in a dehydrated state are less affected than those to whom dehydration is a new phenomenon. I doubt that this will be the case. The fact that dehydration induces increased ADH synthesis and that ADH, ACTH and cortisol all interact would suggest that repeated exposure to dehydration cannot alter this reaction. It may lessen the effect, however, as there will be less of an increase in HPA activity due to emotional responses.

Dehydration also allows the testing of Dietrich's hypofrontality hypothesis (see Chapter 3). The use of fMRI scans on individuals in dehydrated and euhydrated states would allow us to determine whether there are differences in the regions of the brain activated during cognitive tasks. We could also examine whether heat-induced, exercise-induced and exercise plus heat-induced dehydration affect the brain in the same way.

Practical implications

The obvious practical implication is to try to ensure euhydration. We see this during marathon runs where participants are encouraged to drink regularly. In some military situations, however, this is difficult. If soldiers are to maintain euhydration they need to carry more fluid, which increases the load, which in turn increases sweating and dehydration. At this moment in time, I think that there is no real answer to that problem other than try not to go to war.

Team games present difficult problems with regard to rehydration. Many coaches and administrators are ignorant of the difficulties to which dehydration can lead. Team games players are the sportspeople who have to make decisions requiring the use of the central executive and are, therefore, the most vulnerable to the negative effects of dehydration on cognition. Most coaches are aware of the problem when the temperature is high but they should also be aware that dehydration can, and does, occur in temperate conditions. As fitness levels improve, the intensity of team games increases and thus the possibility of dehydration. This leads to another key factor. Coaches should be aware that some drinks are not good for reducing dehydration. Moreover, chemicals as well as fluid are lost in the dehydrated state so solutions such as NaCl are better than water alone. Another factor with rehydrating occurs not only during competition but also after competition. In many games, particularly in Britain, the normal 'rehydration' process involves a 'few beers'. Alcohol is a diuretic and so rather than being rehydrated, the individual may find themselves becoming more dehydrated. Re-education of such sportspeople is vital. Also at professional level, players should be tested for dehydration before training and games. This is a simple test and costs very little. Recently in Britain concern has been shown for ensuring that children remain euhydrated during the schooldays. This is particularly

important if the children are active. Plentiful supplies of fluid should be available in schools.

5.3 Conclusions

Exercise-induced dehydration appears to have a negative effect on some aspects of cognitive function. The effect appears to be consistent where complex central executive type tasks are concerned. Comparatively simple tasks such as choice reaction time appear to be unaffected. Results for short-term memory tasks are not unequivocal but overall suggest a negative effect. That an inverted-U effect is not demonstrated may be because dehydration only occurs when the stress of exercise is high. The commonly made assertion that 2% body mass loss represents a threshold point is debatable, with 1% loss also having a negative effect on several tasks. On the plus side, rehydration has a positive and quick effect with cognitive performance returning to normal very quickly.

6

Exercise, nutrition and cognition

Adam David Cunliffe and Gulshanara Begum

From the outset it can be said that the study of the relationships between nutrition, exercise and cognition represents a fascinating and extremely complex area. Within the broad terms of reference lie an enormous variety of physiological, metabolic and neurochemical processes. This is even before we consider the subjective impressions that accompany these phenomena, which in many cases inform our understanding of cause–effect relationships.

Before deconstructing the components of exercise and cognitive capacity, it is worth considering the functional nature of the link between the two. From an evolutionary perspective it is (as usual) fair to speculate that much of what we observe as scientists in terms of exercise–cognitive capacity linkage bears important relation to utility. Important too is the directionality of the relationship, that is the extent to which exercise influences cognitive function or cognitive function influences exercise.

Teleologically the position that there is a two way dialogue between the physical and the cognitive (with each informing the other), with maintenance of function and capacity of both being important, is most convincing as survival of the human species has depended upon both aspects. Such considerations remind one of the mind–body debate and its emerging futility as we understand more and better the inter-relations between brain and the peripheral body and the inextricable whole they form (Steegmann, 2006).

From the nutritional perspective, systems both cognitive and physical would have to be catered for (Kaplan, 2003). This situation creates opposing demands on the organism – to expend energy to gain nourishment, while at the same time conserving energy to survive times of less nourishment. These opposing demands are reflected in much of the link we find between exercise and cognition. The metabolic and physical characteristics of humans are designed for primal conditions where biology and behaviour were suited to survival in an environmental niche very different from that

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which most people inhabit today (Jequier and Tappy, 1999). The study of the effects of exercise on cognition and the role of nutrition (and maintenance of good nutritional status) offers a unique insight into fundamentals of human function.

It is frequently of considerable use, and also necessity, that we study components of exercise and central drivers of and responses to such in relative isolation. It is useful inasmuch as we can discern with some accuracy the relationships between specific processes and outcomes when we dissect them out from the whole. It is also necessary, as the technology to study the effect of exercise on cognitive function limits much work to studying functional outcomes rather than mechanisms. This is especially true of the central nervous system (CNS). While muscle may be biopsied (Mannion, Jakeman and Willan, 1995; McKenna *et al.*, 1999), blood and urine sampled (Struder *et al.*, 1996; Shirreffs, 2003) and peripheral nerve conduction frequency and velocity measured (Bigland-Ritchie and Woods, 1984), the inner workings of the brain are difficult to study in such detail. Imaging and electroencephalographic techniques give many clues (Gevins *et al.*, 1999), but much hypothesizing and extrapolating from animal models is still invoked with respect to brain function during exercise and in response to nutritional intervention (Bailey, Davis and Ahlborn, 1993; Davis and Bailey, 1997; Anish, 2005).

One clear indication of the dynamic equilibrium that exists between central processes and body systems generally is fatigue and its effects on performance. The processes involved in the genesis of fatigue and the variety of interpretations in understanding these provide many insights into the link between cognition, behaviour and nutritional status, particularly energy balance.

6.1 Fatigue and limits to human performance

The word fatigue has a number of different meanings (St Clair Gibson *et al.*, 2003). Many of these describe sensations, which are a consequence of muscular activity. However, it is also possible to experience fatigue in the absence of muscular activity. Consequently, central to the study of fatigue is the definition that is employed.

Physiologically, fatigue is defined as the inability to maintain power output (St Clair Gibson *et al.*, 2003). The extent of this type of fatigue may appear greater for voluntary contractions than for applied tetanic stimulation indicating a central component (McFadden and McComas, 1996). When examining the relationship between exercise, nutrition and cognitive function, it is convenient to have an anatomical frame of reference by which we separate the CNS (brain and spinal cord) and the exercising body (principally the skeletal muscle system). These are frequently referred to as 'central' and 'peripheral' components, and allow for examination of processes within these compartments to be studied in relation to one another (Green, 1995; Nybo and Secher, 2004). These entities are joined by a chain of command (Figure 6.1), in which the simplest model describes the origin of voluntary muscle activity within higher cortical centres of the brain, first in terms of an 'intent', that is signals which are relayed to the motor cortex and which generate

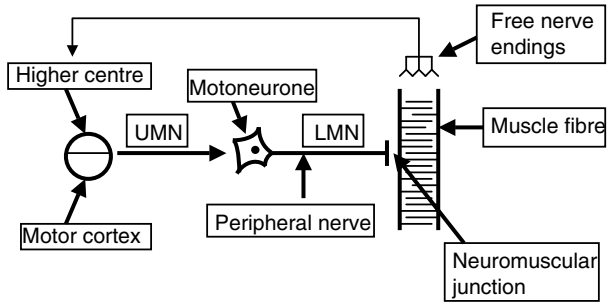

Figure 6.1 Chain of command linking the higher centres with muscular contraction (NB: UMN: upper motor neuron; LMN: lower motor neuron). (Adapted from Jones and Round (1990)).

descending volleys of neural activity through neurons synapsing first at the spinal cord and then again at the neuromuscular junction. Peripheral sensory afferents also relay information back to the brain via the spine with information on movement, temperature, pressure and chemical change within peripheral tissues (Lambert, St Clair Gibson and Noakes, 2005).

Much of this is neurophysiologically verifiable and presents a clear picture of two-way communication. What is less clear are events within the brain in terms of motor drive and sensory processing, and the impact each has on the other (Davis and Bailey, 1997; Nybo and Secher, 2004). In addition, what effects these have on other central processes as diverse as arousal, mood, and speed and accuracy of information processing, is unclear. It is these questions which have formed the basis for much study by investigators, interested in both basic understanding of normal function and also the possibility of modulating processes to produce beneficial effects on human performance.

With respect to biological functionality, the onset of fatigue during exercise may be viewed as an evolutionary safety mechanism (Kay *et al.*, 2001) modulated by many factors to prevent metabolic crisis, preserve the integrity of muscle and other tissues, and in turn prevent the development of injury by forcing a reduction in intensity or even complete cessation of activity (Newsholme, Blomstrand and Ekblom, 1992).

Arthur Bills (1943) classified fatigue into three categories: subjective fatigue (referring to a kind of experience, awareness and/or feeling), objective fatigue (that which is epitomized in studies of work output) and physiological fatigue (referring to the change in certain body processes when performing a task). Today, these categories have many sub-divisions but remain the basis for interpretation of fatigue research. What is clear from research is that in the same situation, whilst some tests of fatigue may show an increase, others may show no change or even a decrease, thus reflecting the complex phenomenon of fatigue (Jones and Round, 1990, Begum *et al.*, 2005; Winnick *et al.*, 2005). Bartley (1976) reported that the commonality between all types of fatigue was 'change' toward deterioration in function, in other words 'incapacitation'. This understanding represents a unified working definition when

investigating fatigue during physical activity and what effects nutritional intervention may have.

Fatigue represents a useful point of study for the investigator interested in mind–body relationships. As a utilitarian phenomenon, fatigue acts to prevent metabolic and physical damage to organisms by limiting activity when metabolite accretion or mechanical strain poses a threat to functional integrity (Vollestad, 1995). Subjectively, an individual experiences fatigue as perceived discomfort (Borg, 1982), an unwillingness to continue with an activity and a change in attitude and motivation towards a task (Parish and Treasure, 2003). Modulation of fatigue states is routinely undertaken through activities such as sleeping, drinking coffee or opening a car window (Sagberg *et al.*, 2004; Childs and De Wit, 2008).

Some forms of modulation give insights into CNS mechanisms underpinning fatigue and limits to performance. For example, drinking coffee allows ingested caffeine to antagonize the action of adenosine in the brain. As adenosine is an inhibitory neurotransmitter, its inhibition allows pro-excitatory systems in the brain greater levels of activity (Dodd, Herb and Powers, 1993). This effect is routinely utilized by millions of people with aims ranging from simply staying alert at work to improving sporting endurance capacity (Armstrong, 2002; Childs and De Wit, 2008). Other nutritional strategies for reducing fatigue (impairment of function) during exercise include pre-loading with carbohydrate, consuming carbohydrate during exercise and the use of ergogenic aids (Winnick *et al.*, 2005; Meeusen, Watson and Dvorak, 2006a). These will be examined in the following discussions.

6.2 Assessing the effects of exercise and nutrition on cognitive performance

Functional capacity in cognitive terms has traditionally been the main means of examining central nervous relationships with peripheral processes. Far from being unsatisfactory this has actually yielded much interesting and practical data. Historically, investigations into mind–body relationships have paid much attention to human productivity; more recently to sporting achievement and to a lesser extent matters of clinical importance. Recent advances in neurobiology have afforded a chance to marry much of the data on CNS function and its role in, and responses to, exercise with neuronal and molecular perspectives (Nybo and Secher, 2004). Nutrition science is a comparatively new discipline, bringing together diverse aspects of biochemistry, physiology and psychology (Cannon, 2002; Cannon and Leitzmann, 2005). This combination of disciplines affords the researcher the opportunity to explore relatively holistic lines of enquiry, in which functional outcomes at the level of human performance or clinical efficacy are frequently key study parameters. The following text will examine briefly some of the main investigative approaches and understandings in this field.

Tests can be broadly divided into those which are objective and those which are subjective. Objective tests being those in which the investigator makes measurements

of function in which the impressions or level of volition of the subject do not impinge on the data gathered (Cunliffe, Obeid and Powell-Tuck, 1997). Subjective tests are those relying upon self-reports and perceptions reported by the test subject (Borg, 1982). For example, a subject is tasked with a 10 km run on a treadmill. Subjective reports of perceived level of exertion can be obtained by simple questioning throughout the trial, while objective measures of blood chemistry can be sampled at the same time (Borg, 1982; Winnick *et al.*, 2005). Investigators can then assess whether correlations exist between the objective chemistry (blood glucose, ammonia or amino acids, for example) and the subjective impressions of effort and fatigue. Comparisons can then be drawn between subjects receiving, for example, glucose-electrolyte beverage or no drink (MacLaren and Close, 2000). This simple type of investigative model is widely used and represents an example of the previously alluded to extrapolation of meaning from events with potential mechanistic significance for CNS function (Zeederberg *et al.*, 1996). Nutritional interventions of many types can be investigated in this way, with investigators cross referencing the parameters they are measuring to look for relationships between physiochemical status, performance and subjective impressions.

Other test modalities fall into a somewhat grey area in that objective quantitative data appears to be produced but elements of subjectivity remain. For example, a simple visual reaction time test relies upon a high level of engagement and motivation in the test subject, and these factors need to be kept equal between subjects and test sessions in order to gain meaning from data (Weiss, 1965; Trimmel and Poelzl, 2006). Other tests such as flicker fusion frequency threshold determination (see below) are somewhat more robust in that the subject has no feel for their level of achievement in the test and therefore is unlikely to be biased by their subjective impression of their own performance (Simonson and Enzer, 1941; Cunliffe, Obeid and Powell-Tuck, 1998). Many of these type of tests, including problem solving and pattern recognition assessments, are subject to a degree of improvement by simple repetition and it is therefore important to familiarize subjects with the test to remove 'learning effects' before active data gathering begins (Sanders, 1998).

There are a number of techniques to measure mind–body connections that have been in use for many years. A good example is the galvanic skin response, widely applied in polygraphy for the detection of lies (Cutrow *et al.*, 1972). Transient autonomic activity, associated with emotion evoking thought, causes fluxes of sweat within (but not necessarily expressed at the surface of) eccrine sweat glands in the hands (Fuller, 1977). Associated electrical changes at the skin surface are readily detected with appropriate equipment and data displayed as wave deflections from baseline conductance values. To the uninitiated it appears that the trace is 'mind reading', as evoking strong images or emotions internally is displayed as clear deflections on a computer screen or paper trace (Grubin and Madsen, 2005). This simple and subtle technique shows how the link between cognition and physiology can be rapidly discerned if one knows where to look.

An early example of investigations of cognitive capacity in connection with both nutrition and physical activity can be found in the work of Simonson and Enzer

(1941). These investigators used a technique involving the ability to discriminate the point at which a flashing light appears to have stopped flashing as the rate of flicker is increased (flicker fusion frequency threshold) (Simonson, 1959). It was found that this objective measure showed considerable sensitivity to physical effort as minimal as the normal activities of a working day, so that by the end of the day a 5 Hz reduction in ability to detect flicker was on average observed (Bartley and Simonson, 1976). The ability to detect flicker fusion thresholds is an interesting example of assessing CNS function in which an understanding of 'wiring' and neural function gives added significance to study findings. The point of 'fusion' has been found to lie in the visual cortex, as this has been shown in animal studies to be the slowest part of the pathway from the retina, through the optic nerve, to the brain (Walker *et al.*, 1943). In other words, a higher (cortical) centre is making what could be termed an executive decision that there is no longer utility (or maybe ability) in discriminating the on/off nature of the stimulus and the light is simply perceived to be on. This measure changes in concert with subjective feelings of tiredness and has been shown also to be sensitive to the effects of drugs, nutritional intake and status, acute bouts of exercise, and is now widely accepted as reflecting cortical arousal (Payne, 1982; Rammsayer and Netter, 1988).

While the type of work described above does localize within the CNS changes that are related to subjective impressions, it does not indicate in neurophysiological terms the reason for the change in function. Given that neurotransmitter release and binding to receptors is the way in which neurons communicate in the CNS (Perry, 2002), considerable thought and work has been carried out in connection with the effects physical activity might have on such phenomena (Meeusen and De Meirleir, 1995; Davis and Bailey, 1997; Meeusen *et al.*, 2001). With respect to cognitive function, we can envisage a simple paradigm in which excitation or inhibition is dominant and hence function either enhanced or inhibited (Olsen, 2002). Where exercise favours release of excitatory neurotransmitters, function is generally enhanced and where exercise favours release of inhibitory neurotransmitters, function deteriorates (Meeusen and De Meirleir, 1995; Newsholme and Blomstrand, 2006). While this appears an attractively simple model, it does not fit well with ecological findings. The adrenergic (excitatory) state induced by anticipation of effort or by strenuous effort itself does seem to enhance cognitive function, but, within a 'window', too much or too prolonged effort or excitement actually having negative effects on cognitive function (Eriksen *et al.*, 2005). This is redolent of homeostatic concepts of ideal zones of physiochemical environment favouring optimal performance (in this case cognitive) and being dependant upon the neurochemical milieu within the brain.

Nutrition intervention alone will do little to spare an anxious pre-event athlete from deterioration in subsequent performance due to over-excitability. However, at later stages of prolonged physical effort, hydration status (Shirreffs, 2003), adequate substrate for adenosinetriphosphate (ATP) production (Nicholas *et al.*, 1995) and effective buffering of metabolites (Vollestad, 1995) may be important factors in maintenance of both physical and cognitive capacity.

The rate of neural firing and neurotransmitter release is of fundamental interest given that within the CNS, these are the defining events in thought and action. Referring again to the chain of command, in which intent is translated to movement, we can utilize nerve stimulation techniques to assess the relative contribution of central and peripheral components of performance as effort continues (Merton, 1954), and fatigue manifests as functional incapacitation and subjective sensations of increased effort/decreased motivation. For example, in a seminal study by Brasil-Neto *et al.* (1993), it was found that transcranial magnetic stimulation of cortical regions the brain, but not electrical stimulation of descending motor neurons in the brainstem, produced decrements in motor evoked potentials (MEPs) measured at target muscle groups. The authors noted that the pattern of decrements in MEPs observed was consistent with fatigue due to neurotransmitter depletion in cortical synapses (based on well-defined studies of patterns of acetylcholine depletion at the more readily observable neuromuscular junction). The decrement in MEPs was also in accord with subjective reports of fatigue, suggesting the possible identification of a site for fatigue in higher brain centres. Given the complex interconnections within the brain, it is easy to envisage how this information could be conveyed to centres involved in multiple other CNS, and hence cognitive, functions.

This model suggests that collateral signalling could affect activity of diverse brain areas and functions. It should also be noted that sensory afferent information returns from exercising muscle, further informing the brain of physiochemical status in peripheral tissues (Jones and Round, 1990). Free nerve endings in muscle have been shown to be sensitive to metabolite accumulation and the presence of algesic agents (Maughan, Gleeson and Greenhaff, 1997). Temperature and proprioceptive sensory information combines with this to relay a complex picture to the brain of the state of active tissue. Thus, equipped with information on local central events and peripheral consequences, the brain can apportion relative resource availability to processing, experiential and motor drive demands of exercise. This hypothetical model integrates motor and sensory activity but importantly also indicates how higher centres are able to produce a subjective experience. It is this subjective element that forms the basis of self-reports, governs levels of motivation and determines behaviour itself.

While much of the above describes modelling exercises, there are arenas in which we find practical application for the study of mind–body relationships. For example, sports science has made tremendous strides in the past three decades and now encompasses physiological, psychological, metabolic and biomechanical perspectives (Nicholas *et al.*, 1999; Begum *et al.*, 2005; Noakes, St Clair Gibson and Lambert, 2005; Winnick *et al.*, 2005). The attenuation of fatigue and the promotion of vigour and motivation are key objectives for sports scientists, and much of the work relates directly to the effect of exercise on cognitive capacity. Many sports require not only speed and strength, but decision-making, accuracy, and spatial awareness and processing capacity (Reilly, 1997; Reilly, 2003).

Football is an interesting case, in which different exercise modes are combined with strategy, teamwork and the need to rapidly adjust to changing spatial and

physical environmental conditions (Reilly, 1997). In a straightforward scenario, a player sees a ball coming towards him/her at high speed. He/she needs to be able to react quickly to control the ball then decide quickly in which direction to pass the ball and execute with precision his/her own pass. Within less than 3 s of physical activity, decision-making and the execution of fine motor skills are in demand. It is interesting to note that the number of mistakes (and likelihood of goals being scored) tends to rise as the duration of a soccer match increases (Reilly, 2003). This raises the question of what has happened during the exercise of match participation that has caused changes in performance. In addition, how can we measure the changes and what possibilities exist to intervene nutritionally to reduce the negative effects of exercise?

6.3 Nutrition, exercise and cognitive performance

Acute effects of food ingestion are easy to observe. Upon consumption of a meal, an individual will report and demonstrate changes in mood, exercise capacity, level of alertness and motivation (Craig and Richardson, 1989). The physiology and chemistry underlying these is complex, reflecting the multiple systems affected by food intake (Chaudhri *et al.*, 2008). The dominant effects are probably the redistribution of blood flow away from skeletal muscle towards the gut and the release of gut hormones (e.g. cholecystokinin), which serve to modulate digestive processes (Woods, 1991) but also produce feelings of satiety and lethargy (Stunkard, 1975). Subjective states are altered too with feelings of satisfaction and disinclination to engage in physical activity being an obvious example. These post-prandial events are functional in promoting digestive efficiency (Hutchinson, 1952; Woods and Strubbe, 1994) but interestingly, in connection with the present discussion, have clear effects on subjective impressions and cognitive processes. Dips in cognitive and physical performance are clear during post-lunch and evening meal tests (Blundell *et al.*, 2003).

Exercise capacity and cognitive function are affected independently by nutritional intake and status (Gibson and Green, 2002; Backhouse *et al.*, 2007; Luchsinger, Noble and Scarmeas, 2007; Noakes, 2007b; Patterson and Gray, 2007). Upon initiation of physical activity, there are also important interactions that take place, particularly according to substrate availability and metabolite accumulation (Winnick *et al.*, 2005). In this way, it is macronutrient status that has the greatest influence on physical and cognitive activity (Lambert and Goedecke, 2003). Food intake per se has important effects on cognition, mood and vitality (Gibson and Green, 2002). This is due to a complex array of factors governing hunger and satiety, digestion and absorption, and multiple post-prandial events involving transport and storage of nutrients (Hutchinson, 1952). More broadly, food acquisition and intake form a complex series of behaviours, highly goal oriented and almost invariably successful!

During exercise there exists a tension between the need to improve functionality, both cognitive and metabolic, and the drive to conserve energy and protect systems

from homeostatic disturbance (Lamb and Brodowicz, 1986; Nybo and Secher, 2004; Mendez-Villanueva, Fernandez-Fernandez and Bishop, 2007). If exercise continues until peripheral energy-yielding substrates (particularly muscle glycogen – as fat stores, even in lean individuals, are extensive in terms of ATP production potential) reach very low levels and/or the accretion of metabolic by-products of ATP production (particularly H^+) accumulate to significant levels, afferent information reaching the CNS induces a subjective state of extreme unwillingness to continue the physical effort (Åstrand *et al.*, 2003; Lambert, St Clair Gibson and Noakes, 2005). In addition, a behavioural shift towards the desire to 'rest' is apparent and maintained until homeostatic balance is restored. In these effects we see the importance of volition in exercise.

Within what is physically possible during exercise, motivation plays a significant role in performance. Exhortation and indeed bribery have been shown to be effective improvers of performance, indicating that the desire to reduce effort significantly precedes the actual cut-off point for exercise capacity as determined by purely physiological and biochemical processes (Schwab, 1953). To avoid the vagaries of volition many researchers of peripheral processes have employed techniques to obviate central inhibition of muscle function (Merton, 1954; McFadden and McComas, 1996). This is readily achieved by peripheral nerve stimulation (PNS) producing a clear picture of the absolute limits of muscle function in terms of both peak force and endurance (Bigland-Ritchie and Woods, 1984; Chan *et al.*, 1986). Findings using PNS suggest that small changes in nutritional state are reflected in the contractile properties of skeletal muscle (Russell *et al.*, 1983; Chan *et al.*, 1986). It should be noted that while such data are important from a pure science perspective they remain largely unhelpful with respect to ecological situations in which free living individuals are engaged in exercise.

The type of biochemical changes (substrate depletion and metabolic accretion) that take place in contracting muscle cells during repeated tetanic stimulation, via peripheral nerves, far exceed those which are observed during voluntary activity (Green, 1995). Such findings give useful insights into physiology but little information on the interplay between central and peripheral processes. What is clear though is that when conducting studies in subjects where volition is a significant factor, there needs to be awareness that level of motivation can be a key determinant of performance. This may explain why the effects of, for example, branched chain amino acid interventions in endurance events produce effects only in non-elite athletes, elite athletes being accustomed to overriding pain and other fatigue cues as part of their training (Van Hall *et al.*, 1995; Watson, Shirreffs and Maughan, 2004). Regardless of this, all individuals will have their exercise capacity reduced to some 50% of their maximum volume of oxygen uptake (VO_{2max}) upon glycogen depletion as reliance upon (slower processes of) fat oxidation predominates (Newsholme, Blomstrand and Ekblom, 1992). This is an example of a metabolic event overwhelming other systems in terms of physical performance. The subjective experience being that which endurance athletes term 'hitting the wall' (Stevinson and Biddle, 1998).

Exercise induced muscle glycogen depletion is an interesting phenomenon in that it is closely linked to subjective impressions of fatigue (Snyder, 1998). The simple expedient of taking sufficient carbohydrate in the diet before exercise can delay the onset of fatigue, and the changes in motivation and performance that are brought about as a result of lack of glucose supply to exercising muscle (Schlabach, 1994). Optimum 'loading' strategies are well established, involving a tapering off from training accompanied by increased carbohydrate consumption in the days leading up to a competitive event (Hawley *et al.*, 1997). In addition, taking carbohydrate during exercise, usually in the form of glucose-containing beverages can also help to preserve glycogen stores and delay fatigue (Winnick *et al.*, 2005; Foskett *et al.*, 2008). There is some evidence, however, that ingestion of a high glycaemic index carbohydrate immediately prior to exercise may produce (in some individuals) rebound hypoglycaemia during exercise due to the elicitation of an insulin 'spike' (Jentjens and Jeukendrup, 2002). Glycogen depletion has a secondary effect during prolonged exercise, which can influence neurotransmitter synthesis rates in the brain (Nybo and Secher, 2004) as described below.

The brain, which is dependent to a large extent on blood glucose (Foster *et al.*, 1998) can only be assured of adequate supply during exercise via the release into circulation of hepatic stores (Felig *et al.*, 1982; McArdle *et al.*, 1999), as muscle glucose stores are not available for release into the systemic circulation. Given the limited amount of glucose in blood at any one time, approximately 4–5 g (Williams, 2007), it is probable that relative hypoglycaemia could affect glucose-dependent CNS processes significantly when hepatic glycogen stores are low (Nybo and Secher, 2004; Williams, 2007). Certainly, we would expect sensitivity to such to be reflected in subjective changes in willingness to maintain performance levels.

Central serotonergic function may be altered during prolonged exercise (Fernstrom, 2005; Meeusen *et al.*, 2006b). This is thought to be mediated via the increased availability of tryptophan for passage across the blood–brain barrier and occurs as its ratio to other large neutral amino acid rises as a result of uptake and oxidation of branched chain amino acids by exercising muscle (Fernstrom and Wurtman, 1971). In addition, there is a displacement of tryptophan bound to plasma albumin, as competition for binding occurs due to rises in circulating free fatty acids upon glycogen depletion (Newsholme, Blomstrand and Ekblom, 1992; Newsholme and Blomstrand, 1995). A similar effect can be produced by the ingestion of pure carbohydrate, promoting the insulin-mediated uptake of branched chain amino acids (BCAAs, valine, leucine, isoleucine), but not tryptophan, to skeletal muscle (Bellisle *et al.*, 1998).

This specific mechanism (and hence the potential to modulate 5-hydroxytryptamine [serotonin] synthesis rates in the brain via changing amino acid precursor availability at the blood–brain barrier) has been investigated extensively in sports science and nutrition research (Van Hall *et al.*, 1995; Struder *et al.*, 1996; Watson, Shirreffs and Maughan, 2004) (Figure 6.2). Tryptophan is converted to 5-HT in the brain via tryptophan hydroxylase at a rate determined by its availability across the blood–brain barrier (Fernstrom and Wurtman, 1971; Fernstrom, 1977). Given that

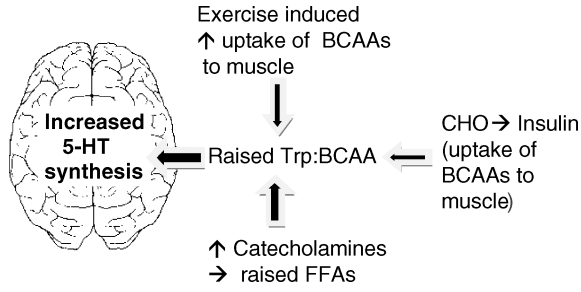

Figure 6.2 Effects of exercise and nutrition on free tryptophan to branched chain amino acid ratio. (NB: BCAA: branched chain amino acids; Trp: tryptophan; CHO: carbohydrates; FFA: free fatty acids; 5-HT: 5-hydroxytryptamine/serotonin).

tryptophan movement across this barrier is in turn determined by its ratio to other large neutral amino acids, efforts have been made to reduce its influx via ingestion of large neutral amino acids (mainly valine, leucine, isoleucine) (Newsholme and Blomstrand, 1995), the rationale being that 5-HT, as an inhibitory neurotransmitter, will promote fatigue and, by limiting its synthesis, fatigue will be limited and performance enhanced (Blomstrand, 2001). Findings from intervention studies, in which endurance runners were supplemented with BCAAs are equivocal (Hassmen *et al.*, 1994; Van Hall *et al.*, 1995), however, and no improvement is apparent in elite athletes (Blomstrand *et al.*, 1991; Van Hall *et al.*, 1995). This suggests that despite the inhibition of central 5-HT synthesis, other systems may predominate in highly motivated individuals. In addition, in the absence of 'brain slice' evidence, it is uncertain whether increased neurotransmitter synthesis rates translate necessarily into increased release rates at relevant synapses (Huether, 1999).

Given the role of 5-HT in mood as well as fatigue, it is possible that feelings of positive affect may ensue when 5-HT levels rise in the brain (Meeusen, 2005), although the so called 'runners high' is probably mediated via a separate pathway, that of endogenous opioid release (Boecker *et al.*, 2008). This occurs during and after prolonged exercise, with the likely function of reducing the discomfort of heavy prolonged physical activity, but also with the result of producing what some athletes describe as a state of euphoria. Aside from these rather specific effects, exercise in general tends to get people out-of-doors, exposed to more daylight and interacting more with others. All these combined have positive effects on mood and it is difficult to discern the relative impact of each.

6.4 Micronutrients, exercise and cognitive performance

While micronutrients (vitamins and minerals) appear to be of less significance in terms of human performance unless a deficiency state occurs, there is a theoretical basis and a reasonable body of evidence to suggest that cognitive function, particularly with respect to mood, can be modulated through ingestion of certain micronutrients

(Bender, Njagi and Danielian, 1990). Most notable in this connection are organic enzyme co-factors, principally B-vitamins concerned with the endogenous synthesis of certain neurotransmitters (Deijen *et al.*, 1992). For example, the synthesis of mono and catecholamines in the brain is dependent upon vitamin-requiring enzyme-catalyzed reactions (Hutto, 1997, Jorm *et al.*, 2006). Tryptophan as a 5-HT precursor and tyrosine as a dopamine/catecholamine precursor are thought to be better transformed if taken with vitamins B-6/12 and folate which are required for the synthetic pathways to proceed (Bender, Njagi and Danielian, 1990). A number of well-controlled studies have shown success in treating depression through the administration of amino acid neurotransmitter precursors in conjunction with vitamins, aiding their metabolism to compounds active in the CNS (Meyers, 2000).

Fatigue, sleep problems and even depression have been noted in individuals suffering from iron deficiency anaemia (Benton and Donohoe, 1999). This deficiency is somewhat over-represented in athletes as haemolysis from impacting hard running surfaces, gastrointestinal blood loss in distance runners, and restrictive diets in aesthetic and weight-restricting sports can all compromise iron status (Chatard *et al.*, 1999). Supplemental iron will remedy dietary deficiency but megadosing with iron does not increase red cell synthesis or improve performance (Rodenberg and Gustafson, 2007). Only training and lower atmospheric oxygen levels promote natural increases in blood red cell and haemoglobin concentrations (Shaskey and Green, 2000) (illegal use of erythropoietin will achieve the same).

Other mineral deficiencies are relatively uncommon and balanced diets adjusted in calories to meet high energy expenditure in training and competition will generally provide adequate quantities (Gleeson, Nieman and Pedersen, 2004). Indeed, hyponatraemia (low plasma sodium), which is frequently a concern to athletes, is normally caused by ingestion of large quantities of plain water during physical activity rather than the magnitude of exercise-induced sodium loss in sweat (Noakes, 2002). If no fluid is taken when sweating heavily, sodium concentrations tend to rise in blood as sodium in sweat is in lower concentration than in plasma (Montain, Cheuvront and Sawka, 2006). Given that osmoregulation is governed by receptors sensitive to concentrations of sodium this (relative hypernatraemia) explains the thirst induced by sweating (Ramsay, 1989). Drinking copious quantities of plain water will dilute the blood, which has lost modest quantities of sodium, and can lead to hyponatraemia via dilution effects (Kovacs and Robertson, 1992). This can result in physical performance deficit, mental confusion, delerium and even death (Barr and Costill, 1989; Noakes, 2002), hence the benefit of ingesting electrolyte-containing fluids during events where significant sweating can occur (Maughan and Noakes, 1991).

The metabolic and physiological roles of other minerals during exercise are largely understood but deficiency rare, and supplementation in nondeficient individuals produces no physical or cognitive performance advantage. Investigators need to take care when looking at plasma levels of vitamins and minerals in sportspeople, as many athletes have significantly expanded plasma volume as a result of training and this can result in apparently low levels of, for example, haemaglobin, a measure of iron

status, when in fact, total circulating quantities are higher (due to training induction of red cell synthesis) than in their sedentary counterparts (Schumacher *et al.*, 2002).

6.5 Nutritional ergogenic aids and cognitive performance

Despite huge sales and much anecdotal reporting of ergogenic benefits of nutritional supplements, very little evidence supports most claims (Williams, 1994; Kanter and Williams, 1995; Williams, 1995). In connection with CNS function, caffeine, as described earlier, has measurable performance-enhancing abilities (Jones, 2008). This is due, in part, to its inhibition of adenosine in the CNS, but also due to peripheral effects in stimulating lipolysis and hence increasing fat oxidation (Graham, 2001; Paluska, 2003; Keisler and Armsey, 2006). The advantage of this being glycogen sparing (Tarnopolsky, 1994), which can delay and reduce the impact of glycogen depletion on the CNS, as described.

Another stimulant, Ma Huang (ephedra) has known anti-fatigue and weight loss properties, but is associated with significant side effects and is a banned substance in competitive sport (Powers, 2001). A range of other herbs, plant extracts and unusual nutritional preparations including ginseng (Vogler, Pittler and Ernst, 1999; Ziemba *et al.*, 1999; Kennedy and Scholey, 2003), cordyceps sinensis (Parcell *et al.*, 2004; Colson *et al.*, 2005) and bovine colostrum (Shing *et al.*, 2006) have been the subject of much research, which has in some cases been flawed by poor study design. While some research evidence does suggest that ginseng can delay fatigue and enhance cognitive function (Kennedy and Scholey, 2003) probably the best evidence for performance enhancement has been produced for creatine.

Creatine increases hydration in muscle and facilitates increased training intensity via increased rates of ATP re-synthesis. A small amount of evidence suggests that creatine may have some effects on cognitive performance, but this observation has only been made in sleep-deprived adults (Rawson *et al.*, 2008). There remain concerns however, over the possibility of kidney damage when creatine is taken in large doses (Bizzarini and De Angelis, 2004).

Many supplements for sport are sold as potentially ergogenic, based on their normal function and the idea that supra-physiological dosing will increase this normal function in a beneficial (to performance) way. For example, carnitine which is involved in the normal shuttling of fatty acids into mitochondria for oxidation (and hence ATP production), is sometimes marketed as a 'fat burner' helping with weight loss and enhancing sports performance (Marconi *et al.*, 1985). This is not supported by evidence, as the amount of carnitine available to the body does not appear to be the rate-limiting factor for fat oxidation (Spriet, Perry and Talanian, 2008). There are many examples of this suggestion that the normal function of a compound can be taken to new levels via high dose administration to enhance performance. Care, therefore, needs to be taken to examine the actual evidence regarding performance (physical and mental) enhancement claims related to nutritional supplements.

6.6 Integration of research observations

Much data gathered indicates that as exercise duration and intensity is increased, there is an augmentation of cognitive processing capacity (Brisswalter, Collardeau and Arcelin, 2002). Improvements are seen in terms of many standard measures of function including reaction time (simple, choice, visual and auditory), pattern recognition and problem solving (Welsh *et al.*, 2002; Begum *et al.*, 2005; Winnick *et al.*, 2005). This is accompanied by paradoxical increases in subjective impressions of fatigue and effort reflecting the dual demands of the need to maintain functional output as work-rate increases and the drive to conserve energy (Noakes, 2007a). Indeed, there is a relatively large performance zone in which perceived effort increases are accompanied by improvements in many typical laboratory tests of cognitive function (Brisswalter, Collardeau and Arcelin, 2002). This may be explained by the concept of 'eustress' in which nearly all task performance is enhanced by moderate physical or mental stress (Selye, 1975).

Excessive physical demands create 'distress' which is characterized by decrements in both physical and cognitive performance (Welsh *et al.*, 2002; Begum *et al.*, 2005; Winnick *et al.*, 2005). Too little demand on physical or mental capacity also gives rise to sub-optimal performance. A relatively normal distribution curve can be drawn for many aspects of human performance against stress and exercise-induced stress frequently follows this pattern (Kerr, 1985).

If cognitive function is improved by moderate exercise and is sub-optimal at lower levels or at very high levels, we may ask what mediates this effect and creates an optimal level of exertion? Furthermore, why have we evolved an adaptive upregulation of function when engaged in exercise? As the body moves faster or makes faster movements, it is clearly important that reaction and response times are decreased to allow proper coordination and interaction with the external world at the faster tempo; likewise, decision-making and recognition of external cues.

Within the brain, the activation of catecholamine release appears to be responsible for much of this 'speeding-up' of processing (Hoshino, 2005). Indeed anticipation of exercise alone can induce central and peripheral adrenaline and noradrenaline release (Mason *et al.*, 1973). In addition to the increased levels of central arousal, catecholamines peripherally can, in concert with the elaboration of other stress hormones, make substrate available for exercise, and induce increases in heart rate and differential vasoconstriction favouring blood flow to skeletal muscle (Nilsen *et al.*, 2007). All these effects are highly functional and serve to optimize neural, metabolic and muscle performance as the body increases its level of exertion. Faster, more efficient processing centrally is synchronized with peripheral adaptations, and combined these effects serve as preparation for, and rapid adaptation to, the increased metabolic and functional demands of exercise.

So far the elements of cognitive function that have been focused on have been widely applied laboratory measures such as reaction time, pattern recognition and problem solving. It would be wrong, however, not to mention mood and subjective

vitality in this discussion as exercise has been shown to have important effects in modulating mood states, physically active individuals tending to be happier and more alert generally than their sedentary counterparts (Scully *et al.*, 1998; Fox, 1999). While some data here is somewhat nebulous and subjective, quantitative and well-controlled studies have been carried out in the form of clinical trials, particularly in the case of chronic fatigue syndrome (CFS). This poorly understood condition is characterized by long-term feelings of tiredness to the point of severe interference with everyday life (Carruthers, 2007). While some clinicians and researchers make a link with post-viral states others consider the condition to be psychologically mediated (Bassi *et al.*, 2008). In connection with the current discussion this difference in opinions gives an interesting insight into the two-way nature of communication between central and peripheral processes. If indeed the CFS is mediated through elements of immunity, such as interleukins, capable of inducing fatigue, amongst other things, this clearly indicates how peripheral and systemic phenomena can lead to powerful subjective (cognitive) central effects. If, on the other hand, the origin of the disorder lies purely in the psychology of the individual, how can we account for the muscle pain and weakness that is associated with the syndrome? In any event, and with respect to exercise, it is interesting to note that exercise has been found to be among the best of therapeutic interventions to date for sufferers of CFS (Nijs, Paul and Wallman, 2008). Until a better mechanistic understanding of the disorder is revealed, we can only speculate as to why this may be. Possible answers are an attenuation of any deleterious immune effects, which are inducing symptoms, or the induction of different central neurochemical states via exercise itself.

The inter-relations between muscle, brain, endocrine and immune systems are as yet not fully understood. What is clear is that there are complex mechanisms for communication between these systems, all of which are activated during exercise. Cognitive function, in the ways it can be assessed, is enhanced as exercise commences. It is, as discussed, advantageous to have this improvement in speed and processing as surrounding environmental cues are approaching more rapidly. In a survival situation, this implies better chances of sustaining life and in a sporting situation, greater precision and accuracy.

At what point then does function start to falter and cognitive capacity show measurable decline? It appears that loss of capacity correlates with self-reports of actual exhaustion rather than fatigue, meaning a prolonged protection of CNS function across a wide range exercise intensities and durations (Claypoole *et al.*, 2001). This reflects the importance of brain function and the relative prioritization (bioenergetically) that it is afforded in the continuum of events leading to exhaustion. It is not clear what exactly leads to the deterioration in cognitive capacity, but it is possible that glucose availability to the brain and/or the ratio of glucose to lactate (and other metabolites) in blood, as sensed by the brain, could be important indicators of 'metabolic fatigue' (Lambert, St Clair Gibson and Noakes, 2005). In addition we must consider the potentially deleterious effect of circulating ammonia, elevated via increased purine nucleotide activity in exercising muscle (Graham and Maclean, 1992), upon reaching the brain. These factors, along with afferent sensory

information from fatigued muscle, could potentially all combine to produce a functional incapacitation of the brain, reflected in reduced task performance witnessed in cognitive function decline at the stage of exhaustion (Davis, 1995). Many inter-individual differences will exist according to fitness level, fuel storage capacity and habituation to effects of exercise (Hawley, 2008). Individuals will differ, therefore, in their ability to maintain function, both central and peripheral, during the course of exercise.

6.7 Challenges in research

The methodological challenges for studying the relationship between exercise and cognitive function are manifold. Brain processes are largely inaccessible and much use is made of studying correlates of such, including metabolites of relevant compounds, where available in blood and urine and occasionally cerebrospinal fluid (CSF). For example, blood glucose measures could indicate changes in availability to the brain, elevated 5-hydroxy-indoleacetate in CSF showing increased 5-HT turnover in the brain and urinary catecholamines indicating the level of circulating adrenaline and noradrenaline (Kennedy *et al.*, 2002; Mujika *et al.*, 2004). All of which are relevant to cognitive capacity, and all of which found to change during exercise (Tatar *et al.*, 1984).

When including the effect of nutrition and indeed nutritional status of subjects, matters are further complicated. Dietary interventions need to be carefully controlled to draw meaning from investigations. For example, when altering the macronutrient composition of a meal, can we be sure that changes in performance or cognitive capacity observed are a result of a new carbohydrate level in the diet, when in order to achieve such, either protein or fat or both will now be in new proportions? In addition, while it may be interesting to assess the effects of pure protein or fat intakes on a range of outcome measures, how realistic is it to ingest highly unpalatable test meals? Also of importance is the habitual diet of a test subject. Metabolic alterations in the rates of uptake, transport and oxidation of macronutrients take place with time according to the relative macronutrient composition of normal meals. Sudden departures from normal eating patterns under test conditions can produce seriously skewed results. Compromise in such complex investigations is commonplace and presents challenges in interpreting study findings.

The array of commonly used tests of cognitive function proves interesting in that the observed parameters do not change uniformly (Brisswalter, Collardeau and Arcelin, 2002). That is, some may improve with exercise while little change or deterioration of others is evident. This indicates to the investigator that it is important not to oversimplify models of brain function during exercise into a unitary phenomenon. While subjective measures of tiredness may show earlier signs of deterioration, objective measures of reaction speeds and processing capacity may be improved above pre-exercise baseline until a point close to complete exhaustion (Davranche *et al.*, 2005a).

Through studying the relationships between central and peripheral events during exercise much data has been made available. From these it is clear that communication between the CNS and the exercising body is dynamic and two-way. Both cognitive function and exercise capacity improve up to a point determined by exercise duration and intensity, after which declines in both become evident. Some comparison can be made here with the effects on physical and cognitive function when food deprivation occurs, albeit over a longer timescale. Initially levels of alertness and motivation are raised as hunger increases (Wurtman, 1979). Mood is altered too – a hungry man being an angry man. Finally, when nutritional status is seriously compromised so is physical and mental ability (Katzman *et al.*, 2001). The unifying theme being the drive to maintain systemic balance and retain important body reserves of energy. As a practical example, we can see that for primitive man, a lengthy and exhausting but productive hunt was well worthwhile if the reward was a supply of calories far outweighing that energy that had been expended (Chakravarthy and Booth, 2004).

The creation of valid protocols, which take into account issues of volition and motivation, are an important consideration when investigating mind–body relationships during exercise. In this connection, bi-directional measurements can enhance our understanding of the flow and significance of information between brain and body. Nutritionally, it is vital that interventions are clearly described in terms of macro- and micronutrient intake and relative change from baseline eating habits.

A continuing challenge in this area of research is to ascertain the level of fit between hypothetical models and the 'real world' data gathered in investigations. Many applications for research findings exist in industry, medicine and sports science, all arenas in which practical significance can be found for knowledge gained.

6.8 Conclusion

The links between exercise, nutrition and cognitive capacity are functional in nature, protecting energy reserves and tissue viability. Afferent sensory feedback regarding metabolite accretion, as a function of muscular activity is integrated with collateral signalling information in the CNS to produce unconscious and conscious profiles of cost–benefit ratios relating to effort. Translated to subjective experience, we find perceptions of fatigue and changing levels of motivation. Functionally we can measure physical and cognitive capacity across a range of exercise durations and intensities, optimum performance for the most part being found at moderate levels of exertion. Nutritional strategies optimizing carbohydrate storage and slowing rates of glycogen utilization are the best understood means of maintaining both physical and cognitive capacity during exercise. In addition to functional capacity, biochemical correlates of substrate utilization and neurotransmitter precursor availability provide useful insights into phenomena affecting both exercise capacity and cognitive function.

7

A chronometric and electromyographic approach to the effect of exercise on reaction time

Karen Davranche and Michel Audiffren

In many sports, competitors are under time pressure and must make tactical decisions very quickly. Especially in team sports, fighting sports and racket sports, the ability to give an accurate and appropriate response in a short time determines success. Moreover, in the field of physical activity, athletes are faced with physiological and cognitive demands and must simultaneously deal with both of these requirements in order to achieve a good result. Thus, the improvement of the knowledge concerning the interactions between physiological and cognitive processes appears to be particularly relevant to the framework of cognitive psychology, and sport and exercise sciences. In the following paragraphs, we will focus our attention on how exercise alters decision-making performance under time pressure.

The effects of exercise on decision-making performance have been studied using a wide variety of cognitive tasks and many physiological interventions during recent years. Unfortunately, the diversity of the protocols has led to many equivocal results and considerable differences in experimental protocols have made the synthesis and the comparison of results difficult. However, this multitude of experiments gives the opportunity to identify the weakness of such protocols and to point out the necessity of using a rigorous methodology to avoid interfering variables (e.g. learning effect, exercise workload, number of trials, time on task). Presently, there is a consensus among researchers examining the effect of exercise on cognitive function.

The mental chronometry method is certainly the most widespread method used to assess the effects of exercise on cognitive processes. The paradigm of mental

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chronometry takes into account the fact that the cognitive processes can be assessed through the measure of the duration of the information processing. Indeed, a number of inferences can be made using the measure of reaction time (RT). RT corresponds to the time that elapses between the onset of a stimulus and the occurrence of an overt response. The mental chronometry method consists of measuring RT in different conditions and, all other things being equal, the RT modulations are used to make inferences. Most authors agree that RT corresponds to the time necessary to perform a series of stages (a stage being a functional set of elementary operations), which begin at the onset of the response signal and which end at the occurrence of the response. Thus, RT can be broken down into a series of stages (Anderson, 1980). Van der Molen *et al.* (1991), for instance, proposed a six-stage breakdown of information processing: three perceptual stages (stimulus pre-processing, feature analysis and stimulus identification); a central stage (response selection); and two motor stages (motor programming and motor adjustment).

In the context of exercise and cognitive processes, despite the fact that results are not unequivocal, several studies suggest that RT is shorter when the participants perform an RT task while simultaneously undertaking sub-maximal exercise than when they are at rest (e.g. Arcelin, Delignières and Brisswalter, 1998; Chmura *et al.*, 1998; Davranche *et al.*, 2005a; McMorris and Graydon, 1996a; Paas and Adam, 1991; Pesce *et al.*, 2002; Yagi *et al.*, 1999). However, the questions of how exercise exerts its influence on mental processing and what stages are affected by physical exercise are still unclear.

The nature of the stages altered by exercise has so far been addressed using the additive factor method (AFM, Sternberg, 1969a, 2001). The method is more extensively presented in Chapter 1 of this book. This inferential method relies upon the analysis of the pattern of statistical effects of factorially manipulated variables: if the effects on RT are additive, it is likely that the variables affect different stages; conversely, if the effects interact, it is likely that the variables affect at least one common stage. Using this logic, Arcelin, Delignières and Brisswalter (1998) and Davranche and Audiffren (2004) have shown that the effect of physical exercise is additive on mean RT, with effects on signal quality, stimulus-response compatibility and foreperiod duration. This suggests that physical exercise spares the stages of stimulus identification, response selection and motor adjustment. These results are, however, quite inconclusive because these experiments failed to unequivocally localize the effect of exercise on information processing. Indeed, the interpretation of a lonely additive statistical pattern is a little problematic because this interpretation is based on an absence of a significant interaction. The unsuccessful use of the AFM implies that more direct measures should be used in conjunction with mental chronometry to assess the influence of exercise on human information processing.

To this aim, electrophysiological techniques (e.g. single neuron activity, electrical and magnetic stimulations, Hoffman reflex) can be used to make inferences based on the observation of physiological changes. The general principle is to combine electrophysiological and mental chronometry techniques in order to record new indices related to the nature and the organization of the cognitive processes. Thus, the locus of the effect of an experimental factor can be addressed using fractionated RT

with respect to the changes in electrophysiological activity (Hasbroucq *et al.*, 2002). Note that this chronometric method cannot be used with all physiological indices. Indeed, because of the way in which the electrophysiological changes are measured, the onset of the physiological activity must be estimated using a trial by trial detection. This method, for example, cannot be applied to the electroencephalography technique when the detection of the event related potential, trial by trial, is impossible because of the background brain activity. Indeed, given the fact that the amplitude of an event-related potential evoked during a trial is weak and variable, it is necessary to make an average of several tens of trials to highlight an event-related potential. The time onset to the physiological change is then estimated, more or less precisely, by using the onset of the physiological change observed on the average curve. However, this estimation is not obviously identical to the average of the onset of the physiological changes that could be observed during a trial by trial analysis.

The electromyographic (EMG) activity of the response agonists allows such a fractioning. The time interval between the onset of the response signal and the onset of EMG activity is termed premotor time (PMT), while the time interval between the onset of EMG activity and the onset of the required motor response is termed motor time (MT) (see Figure 7.1).

MT reflects the duration of the actual execution of the response, which constitutes the neuromuscular component of the motor adjustment stage, whereas PMT reflects the duration of all preceding processes (i.e. perceptual and central stages). By examining the effect of an experimental manipulation on PMT and MT, it is possible to determine whether the manipulation's effects on RT occur after or before EMG onset and, therefore, whether it affects response execution and/or processes occurring upstream in the information flow.

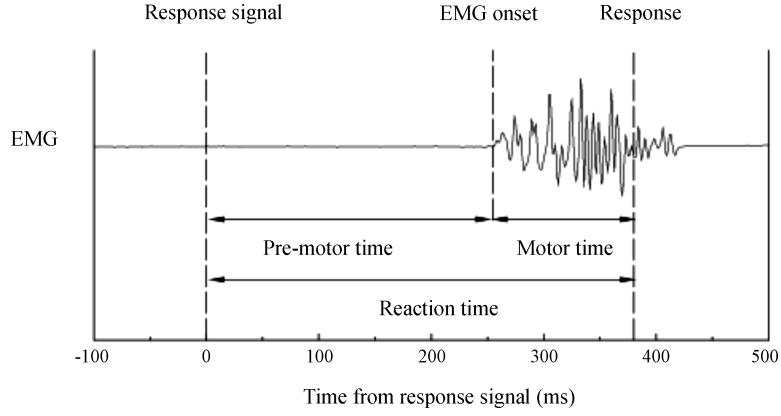

Figure 7.1 Electromyographic activity in the agonists muscle involved in the task as function of time (in ms) from the presentation of the response signal. The reaction time corresponds to the time between the response signal and the onset of the required motor response, the premotor time to the time elapsed from the response signal to the electromyographic (EMG) onset, and the motor time to the time elapsed from the EMG onset to the onset of the required motor response.

Based on this framework, two RT experiments (Davranche *et al.*, 2005a, 2006b), one using a choice RT test and the other using a simple RT task, were carried out and the EMG activity of the response agonist muscle was used to sub-divide the RT into PMT and MT. The purpose of both studies was to decipher whether sub-maximal physical exercise alters the later processes related to the response execution and whether it alters the processes located upstream from the neuromuscular level.

7.1 Research

Methods

During each experiment, 12 subjects, who regularly practised sport, were tested. The subjects performed three consecutive blocks while cycling at 50% of their maximal aerobic power with a freely chosen pedal rate and three consecutive blocks at rest. The order of exercise and rest was counterbalanced across subjects in order to avoid any eventual learning effect. The three consecutive blocks (204 trials) lasted about 15 minutes and a resting period (about 10 minutes) was given to the subject between the exercise conditions.

Subjects were seated on a cycle ergometer, their arms rested on a foam rubber support. In front of the subject, a row of light emitting diodes (LEDs) were positioned at a distance of 60 cm. Two response keys were fixed on the handlebars of the cycle ergometer, one on the right and one on the left, and subjects were asked to respond as quickly and accurately as possible to the visual stimulus by pressing the appropriate key with their thumb. During the choice RT task, the left key was to be pressed in response to the illumination of the left stimulus and the right key in response to the right stimulus. During the simple RT task, only one central stimulus appeared and the response was given by pressing the right response key.

The EMG of the flexor pollicis brevis of each thumb was recorded by means of paired surface Ag–AgCl electrodes, 11 mm in diameter, fixed 2 cm apart on the skin of the thenar eminence. This activity was amplified (gain 10 000), filtered (low frequency cut-off 10 Hz, high frequency cut-off 1 kHz) and digitized on-line (2 kHz). The experimenter continuously monitored the EMG signal in order to avoid background activity as much as possible. If the signal became noisy, the experimenter asked the subject to relax his/her muscles. During the data treatment the EMG traces were inspected off-line, trial by trial, as displayed on a computer screen. Since human pattern recognition processes are superior to automated algorithms (van Boxtel *et al.*, 1993), we hand-scored the EMG onsets. Importantly, at this stage the experimenter was unaware of the exercise condition and of the signal intensity condition he was looking at.

Results

As we might expect, RT was faster in the exercise condition than in the rest condition in both choice and simple RT tasks (Table 7.1). Additional analyses on the percentage of decision error showed that the differences observed on RT are not explained by a

Table 7.1 Mean and standard deviations (SD) of heart rate, overall reaction time and percentage of decision error at rest and during exercise in the choice reaction time (CRT) and simple reaction time (SRT) tasks.

Variable	Mean (SD)			
Task	CRT		SRT	
Condition	Rest	Exercise	Rest	Exercise
Heart rate (bmp.min^{-1})	75 (11)	141 (15)	75 (13)	137 (17)
Reaction time (ms)	275 (26)	262 (28)	226 (19)	217 (22)
Error (%)	0.09 (0.01)	0.17 (0.01)	0.13 (0.01)	0.26 (0.02)

possible shift in the speed–accuracy trade-off. Note that in the simple RT task, decision errors corresponded to responses given in catch trials during which no movement was required.

The fractionating of RT into PMT and MT with respect to the onset of EMG activity of the response agonist shed light on the processes affected by exercise. Indeed, both experiments showed that exercise improved late motor processes (Figure 7.2). These findings suggest that sub-maximal exercise affects response execution and, thus, the neuromuscular component of the motor adjustment stage. This conclusion is strengthened by closer analysis of the EMG activity of the response agonists.

The EMG burst measured through the α angle, which corresponds to the angle comprised by the EMG activity baseline and the line that joins the onset and peak of the rectified EMG activity waveform, was steeper during exercise than at rest

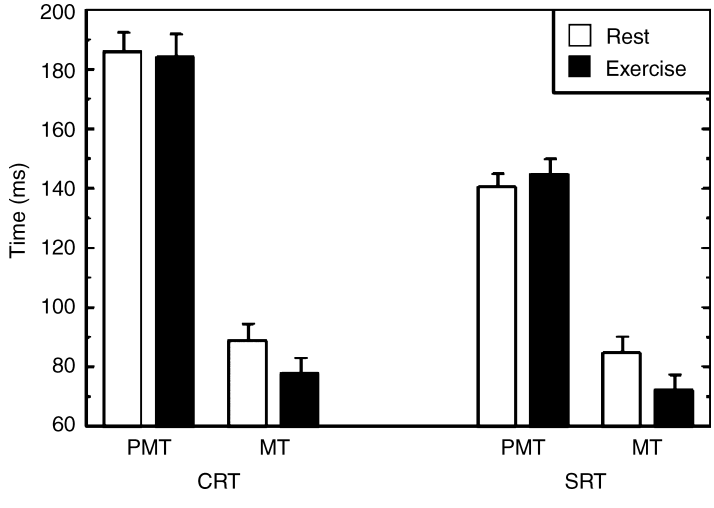

Figure 7.2 Effect of exercise (ms) on premotor time (PMT) and on motor time (MT) during choice reaction time (CRT) and simple reaction time (SRT) tasks. White bars correspond to the performances at rest and black bars to the performances during exercise.

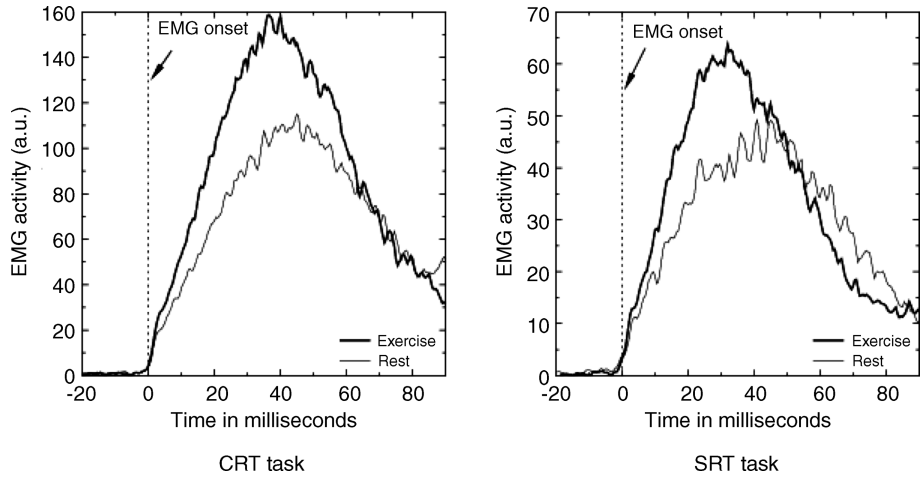

Figure 7.3 Grand average of electromyographic (EMG) activity for the choice reaction time (CRT) and simple reaction time (SRT) tasks during exercise (black lines) and rest (grey lines). The origin of the abscissa is set at the onset of the EMG activity (time 0). EMG is expressed in arbitrary units.

(see Figure 7.3). According to models of EMG and/or force production, the steepness of the EMG activity may be related to the variance of the motor unit onset time: the lower the variance, the more synchronized the motor unit discharges, and the steeper the EMG activity (Meijers, Teulings and Eijkman, 1976; Ulrich and Wing, 1991). In other words, the cortico-spinal command was more efficient during exercise than at rest, which accounts for the effect of exercise on the MT.

Further examination also showed that the surface under the averaged curve during the interval separating the onset and the peak of the EMG activity burst was larger during exercise than at rest. Since the force generated by a muscle is monotonically related to this index (Bouisset and Matton, 1995), the force produced during this time window was larger during exercise than at rest. Considered together, the whole pattern of results clearly converges in suggesting that physical exercise shortens RT by affecting late motor processes. At least three mechanisms could explain the effect of exercise on MT: (1) an increase in conduction velocity induced by an elevation of body and skin temperature; (2) a change in the motor command (firing rate or number of motor neurons involved in the command); and (3) an improvement in muscle contraction at the sliding-filament level.

Even if the effect of exercise is absent on the PMT component, one must note that an interaction between exercise and signal intensity was observed on mean PMT during both experiments. According to the AFM, this finding strongly suggests that physical exercise exerts an effect, although complex, on sensory processes. This interpretation should await further investigations, but the result is compatible with previous findings obtained with the critical flicker frequency (CFF) technique. Indeed, the CFF threshold, which is considered to reflect changes in sensory

sensitivity, has been reported to increase immediately after moderate (Davranche and Audiffren, 2004; Davranche and Pichon, 2005) and exhausting exercises (Davranche and Pichon, 2005).

7.2 Conclusion

These EMG studies confirm that RT performance is better when the task is performed while simultaneously undertaking sub-maximal exercise (50% of maximal aerobic power) than when it is performed at rest. The most important finding of these experiments is that fractionated RT sheds light on the processes affected by exercise.

Indeed, the fractionating of RT into PMT and MT, with respect to the onset of EMG activity of the response agonist, showed that most of the effect of exercise was exerted on the MT component but exercise exerts little influence on PMT. Previous studies using the same methodology have shown that some task variables, such as stimulus–response compatibility, affect only the PMT, while others, such as response repertoire or foreperiod duration, affect both PMT and MT. To our knowledge, exercise is so far the only task variable which affects mainly MT. This is an instance of a double dissociation, which suggests that the two variables are independent. Although relatively simple, the fractionating of RT, with respect to the EMG activity of response agonists, can provide useful information relative to the locus of RT effects and their functional mechanisms.

Finally, the EMG technique used in these experiments deserves some comments. Because the inferences are based on the observation of physiological changes, the main weakness of this technique is naturally the accuracy with which we are able to detect electrophysiological changes. The use of rigorous and systematic methods widely determines the relevance of the results. Moreover, particular precautions must be taken when the electrophysiological changes are observed during exercise because the experimental conditions are not optimal and the sweating function could disturb the EMG signal performed with such surface electrodes. Indeed, without a meticulous method to record EMG, the background activity induced by physical exercise could not allow an unequivocal determination of the beginning of the EMG activity.

8

Acute aerobic exercise effects on event-related brain potentials

Charles H. Hillman, Matthew Pontifex and Jason R. Themanson

The study of acute exercise effects on neurocognitive function has grown in interest over recent decades, largely due to an increasing focus on the relationship between health behaviours and brain and cognition. For example, recent evidence suggests that aerobic fitness is related to better academic performance on standardized tests in grade school children (Castelli *et al.*, 2007). Other research has indicated that adults are able to better engage and classify information in their stimulus environment and process this information more quickly following acute aerobic exercise (Hillman, Snook and Jerome, 2003). Such findings have generated interest in the amount, intensity and duration of exercise necessary to improve cognitive function, with the hope of determining a practical application for improvements in cognitive performance.

Examination of the neuroelectric system has also become increasingly popular in the investigation of acute exercise effects on cognition because the various measures provide a more sensitive means of determining which underlying processes are affected by acute exercise, beyond that of overt action. That is, the temporal sensitivity of neuroelectric measurement allows for the investigation into a sub-set of processes that occur between stimulus encoding and response production. As such, these measures enable researchers to more precisely gauge the effects of acute exercise on cognition relative to task performance measures. Accordingly, this approach allows for an increased understanding of the means by which acute exercise improves cognitive health and effective function.

The purpose of this chapter is to describe a small body of research focused on the effects of acute, aerobic exercise on an aspect of the neuroelectric system, known as event-related brain potentials (ERPs). The scope will be further limited

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to endogenous aspects of the neuroelectric system; that is processes independent of the physical properties of the stimulus environment that are driven by internal cognitive states. We will not engage in lengthy discussion of the various theoretical perspectives since these viewpoints are described earlier in this volume (see Chapters 1 and 3). Rather, the purpose herein is descriptive with the goal of forming a cohesive understanding of a body of literature that investigates acute exercise effects on aspects of the neuroelectric system. We will, however, engage in discussion of executive control because it provides a guiding framework for what is, at times, a seemingly disparate body of literature.

For example, at first glance, two similar studies yield contrasting findings (Pontifex and Hillman, 2007; Yagi *et al.*, 1999); however, upon deeper inspection the disparate findings are understandable and may even be predicted because they require different cognitive processes that involve different neural networks. Unfortunately, as discussed at the end of this chapter, often studies investigating acute exercise effects on the neuroelectric system do not consider how the relationship will be affected by the cognitive task employed. That is, considerable thought is given to the exercise intervention, while considerably less thought is given toward the aspect of cognitive function and the supporting brain tissue involved in the sub-set of processes studied. Several well-written reviews describing how the nature of the exercise stimulus affects cognition have been published previously (Kamijo, in press; Tomporowski, 2003b), but arguably these reviews do not engage in an in-depth discussion of the cognitive neuroscience involved in the various tasks employed. The goal of this chapter is to turn our attention toward the neurocognitive processes affected by acute exercise. Thus, one limitation of this chapter is that the aerobic exercise intervention will not be considered in great detail, despite the fact that the interventions differ considerably across studies.

Accordingly, research examining neuroelectric correlates of exercise and cognition have proceeded in two directions. The majority of studies have employed simple stimulus discrimination tasks, which are described below in detail. Although these tasks are well-grounded in previous neuroelectric literature and have provided insight into exercise effects on cognition, they have provided a fairly limited understanding of the underlying neural networks that support cognitive change. Alternatively, empirical investigations in our laboratory examined a selective aspect of cognition referred to as 'executive control' or 'cognitive control'. These investigations have been further aimed at a selective aspect of executive control, known as 'interference control'. Thus, through the standardization of cognitive tasks and measurement techniques, we are able to draw reasonable inferences that are linked to a specific neural network that supports the sub-set of processes involved in interference control. Through our study of the neuroelectric system, we are able to better elucidate that those processes are influenced by acute exercise and make inferences based on neuroimaging research regarding the brain tissue underlying these processes.

8.1 Executive control

Executive control describes a sub-set of cognitive processes associated with the selection, scheduling and coordination of the computational processes that are responsible for perception, memory and action (Meyer and Kieras, 1997; Norman and Shallice, 1986). Executive processes are functionally distinct from the processes they organize and require conscious awareness (Rogers and Monsell, 1995), which prevents those tasks requiring executive control processes from becoming automatic or habituating over time.

Within the framework of executive control is a sub-set of executive processes responsible for adjustments in perceptual selection, biasing of responses and on-line maintenance of contextual information often referred to as cognitive control (Botvinick *et al.*, 2001). These cognitive control processes are often associated with a 'central executive' in many theoretical models (Baddeley, 1996a; Norman and Shallice, 1986) and this executive is responsible for the adaptability of the cognitive system. The cognitive control processes underlying the adaptability of the cognitive system are not unitary and need to be understood, not only in terms of what increased control does to an individual's interaction with the environment, but also how increased control is recruited and implemented under the appropriate circumstances. To address these issues, researchers have suggested that there are at least two dissociable systems of cognitive control termed 'regulative' and 'evaluative' (see Botvinick *et al.*, 2001 for review).

The regulative system exerts top-down control during ongoing information processing. That is, flexible adjustments in strategic support are provided for task-relevant interactions with the stimulus, allowing for improved attentional maintenance of task demands and representations. Thus, this is the aspect of cognitive control related to how alterations in top-down support alter an individual's behaviour and the quality of their environmental interaction. Available neuroimaging research indicates that this regulative support is likely provided, at least in part, by the dorsolateral prefrontal cortex (DLPFC) (MacDonald *et al.*, 2000).

The evaluative system of cognitive control monitors for instances of behavioural conflict during information processing. More specifically, the evaluative system detects the occurrence of conflict during cognitive processing of environmental information and sends signals to the processing centres responsible for compensatory adjustments of top-down control necessary to successfully adapt to specific task demands (Botvinick *et al.*, 2001). Neuroimaging research has suggested that the anterior cingulate cortex (ACC) is involved in the evaluative system of cognitive control and the signalling/detection of conflict. Most notably, results indicate that ACC activation is largest when cognitive control is weak and conflict is at its greatest due to specific task demands or constraints (Botvinick *et al.*, 1999; Carter *et al.*, 2000; Yeung, Botvinick and Cohen, 2004). Further, increased ACC activation in conjunction with weak cognitive control may indicate the increased signalling for adjustments in control to more strongly engage the strategic processes necessary

to improve subsequent behavioural interactions with the environment (MacDonald *et al.*, 2000).

Thus, the two components of cognitive control interact as part of a feedback loop to optimize task performance (MacDonald *et al.*, 2000). In this loop, the DLPFC implements cognitive control for novel or complex task-related behaviours and the ACC monitors for conflict during task execution. If conflict is present, the ACC signals for an up-regulation of cognitive control. The DLPFC responds to the conflict signal from the ACC with an adaptive adjustment to increase the engagement of control during task execution in an attempt to improve subsequent behavioural interactions with the environment.

8.2 Neuroelectric measurement

Although behavioural measures of performance have been useful in evaluating aspects of cognition, the evaluation of ERPs has provided additional insight into underlying mechanisms that occur during cognitive operations. ERPs refer to a class of electroencephalographic activity that occurs in response to, or in preparation for, a stimulus or response (Coles, Gratton and Fabiani, 1990). This neuroelectric activity is reflective of the synchronous activity of large populations of neurons (Hugdahl, 1995). ERPs can be obligatory responses (exogenous) or reflect higher-order cognitive processing that often requires active participation from the subject (endogenous) (Hugdahl, 1995). The stimulus-locked ERP is characterized by a succession of positive (P) and negative (N) components, which are constructed according to their direction and the relative time that they occur (i.e. N1-P2-N2-P3) (Hruby and Marsalek, 2003). Among the various stimulus-locked ERPs, the P3 has captured considerable attention because it is easily identifiable and has been linked to various cognitive processes during a variety of cognitive tasks. For more extensive descriptions of the stimulus-locked ERPs, the interested reader is referred to reviews by Coles and Rugg (1995) and Coles, *et al.* (1990).

P300

Originally discovered over four decades ago by Sutton *et al.* (1965), the P300 (also referred to as the P3) is a positive-going waveform that peaks approximately 300–800 ms after stimulus onset. This endogenous component reflects neuronal activity underlying basic cognitive functions such as attentional resource allocation (Donchin, 1981; Polich and Kok, 1995). The P300 is considered a cognitive neuroelectric phenomenon as it is elicited in tasks that require the participant to attend to and discriminate between different stimuli (Polich and Kok, 1995). The P300 (and other ERP components) may be decomposed according to amplitude and latency.

P300 amplitude, which is usually measured as the change in voltage from pre-stimulus baseline activity to the largest positive peak after the N1-P2-N2 complex, generally shows a spatial scalp distribution with increasing amplitude from frontal

to parietal electrode sites and lateral to midline electrode sites in young adults (Polich and Kok, 1995). P300 amplitude is reflective of the amount of attentional resources allocated towards a stimulus or task, with increased amplitude reflecting increased attention (Kok, 2001; Polich, 1987; Polich and Heine, 1996). P300 latency, which is defined as the time from stimulus onset to the maximum positive amplitude within a specified latency window (Polich and Kok, 1995), is considered to be a measure of stimulus identification and classification speed (Kutas, McCarthy and Donchin, 1977; Magliero *et al.*, 1984) that is independent of response selection processes (Duncan-Johnson, 1981; McCarthy and Donchin, 1981). It should be noted that shorter latencies are related to superior cognitive performance as P300 latency is negatively correlated with mental function (Emmerson *et al.*, 1989; Howard and Polich, 1985; Johnson, Pfefferbaum and Kopell, 1985; Polich and Martin, 1992; Polich, Howard and Starr, 1983).

Much of the literature on exercise-induced changes in cognitive function has focused on task performance measures (i.e. response speed and accuracy) to gain an understanding of the effects of exercise on behaviour. However, a growing number of researchers are turning towards neuroelectric measures, and particularly the P300 component, to measure underlying neurocognitive function as a means of elucidating why exercise influences behaviour. This approach has become particularly popular with regards to examining chronic physical activity behaviours and cardiorespiratory fitness (Hillman, Buck and Themanson, in press).

8.3 Event-related brain potentials during exercise

Relatively few studies have attempted to examine ERPs to assess underlying changes in cognitive function during acute exercise (i.e. Yagi *et al.*, 1999; Grego *et al.*, 2004; Pontifex and Hillman, 2007), with only a single study examining other ERP components in addition to the P300-ERP (Pontifex and Hillman, 2007). Table 8.1 provides a brief description of the existent literature on the changes in ERP function during acute exercise. Two of these studies have examined the P300 using various versions of the oddball task (i.e. Yagi *et al.*, 1999; Grego *et al.*, 2004). This task requires participants to discriminate between two stimuli with differing probabilities and to respond selectively to the infrequent stimulus, while ignoring the more frequent stimulus. That is, through instruction, a behavioural response is mapped to the infrequent (target) stimulus, while no response is mapped to the frequent (nontarget) stimulus. Finally, only a single study has attempted to assess changes in executive control function during acute exercise (Pontifex and Hillman, 2007).

Despite the fact that both Yagi *et al.* (1999) and Grego *et al.* (2004) have used similar tasks to assess stimulus discrimination during acute aerobic exercise, they have provided conflicting results, since one study reported a reduction in P300 amplitude and shorter P300 latency during exercise (Yagi *et al.*, 1999), while the other reported an increase in P300 amplitude and longer P300 latency during exercise (Grego *et al.*, 2004). Specifically, Yagi *et al.* (1999) examined changes in stimulus discrimination

Table 8.1 Summary of studies performed to assess the effects of acute in-task exercise on neuroelectric indices of cognition.

Author(s)	*n*	Time of test	Exercise intervention	Cognitive task	Result
Grego *et al.* (2004)	12 trained cyclists	Pretest, 3 min, 36 min, 72 min, 108 min, 144 min, immediately post, 15 min post.	180 min cycling at approximately 66% of VO_2max.	Auditory oddball task	Increase in P3 amplitude at minutes 72 and 108, which remained elevated through the 144th minute. Steady increase in P3 latency during exercise, with significantly longer latency at 108 and 144 min following the start of the acute bout.
Pontifex and Hillman (2007)	41 college students	During and rest	6.5 min cycling at 60% HRmax	Modified flanker task	Decrease in N1 amplitude at parietal sites, increased P2 amplitude at frontal and central sites, reduction in N2 amplitude at all sites, and increased P3 amplitude at frontal and bilateral sites during exercise relative to rest. Longer N2 and P3 latencies during exercise relative to rest.
Yagi *et al.* (1999)	24 college students	Pre-test, during, and post-test	10 min cycling at an HR between 130 and 150 bpm.	Auditory and visual oddball tasks	Decrease in P3 amplitude and shorter P3 latency during exercise relative to a pre-test baseline.

during acute, aerobic exercise using both auditory (1000 Hz nontarget tone, 2000 Hz target tone) and visual (white 'X' nontarget stimulus, white 'O' target stimulus) oddball tasks presenting nontarget and target stimuli at a ratio of 80 : 20, respectively. As mentioned above, they observed a reduction in P300 amplitude and shorter P300 latency during both oddball tasks while participants exercised on a cycle ergometer at a heart rate between 130 and 150 bpm relative to a resting, baseline session. Given that P300 amplitude to an oddball task is an index of resource capacity (Kok, 2001) and is related to attentional allocation during working memory operations involved in contextual updating of the stimulus environment, and P300 latency is related to stimulus evaluation and classification speed, their results suggest that, regardless of stimulus modality, individuals exhibit a reduced capacity to allocate attentional resources, but a facilitation of cognitive processing speed during exercise (Yagi *et al.*, 1999). Stated another way, Yagi *et al.* (1999) data indicate that individuals have a smaller capacity to allocate attentional resources, but process environmental information more quickly while they are engaged in aerobic exercise. Taken together, we might speculate that these measures suggest a cognitive strategy aimed at emphasizing the speed of stimulus acquisition at the cost of the quality of stimulus engagement. Given that task performance did not change, it is not possible to know whether these P300 changes were facilitative, reflecting neuroelectric efficiency, or whether exercise was detrimental to individuals' cognitive capacity to engage changes in the stimulus environment.

Alternatively, Grego *et al.* (2004) attempted to examine changes in stimulus discrimination during long duration, acute, aerobic exercise at approximately 66% of their maximum volume of oxygen uptake (VO_2max) using an auditory oddball task (1000 Hz nontarget tone, 2000 Hz target tone), which presented nontarget to target stimuli at a ratio of 80:20, respectively. During acute exercise Grego *et al.* (2004) observed an increase in P300 amplitude after an hour of exercise (at minutes 72 and 108), which remained elevated through to the 144th minute. P300 latency increased steadily during the exercise session, and became significantly longer at minutes 108 and 144. However, it should be noted that the authors chose to assess changes across time relative to the third minute of exercise, rather than relative to the nonexercise pre-test. It is not readily apparent why a time point that occurred after the initiation of exercise was used for comparison; particularly as inspection of the means indicate that P300 latency increased approximately 51 ms between the pre-test and the third minute of the exercise intervention, 111 ms from pre-test to minute 36, and 132 ms from pre-test to minute 72. Regardless, the data suggest that alterations in P300 occurred throughout the course of the exercise intervention, although statistical significance was not achieved at all time points. These data are in stark contrast to those of Yagi *et al.* (1999) as an increase in P300 amplitude occurred after 36 min of exercise and longer P300 latency occurred after only 3 min of exercise. If we were to draw conclusions based solely on the Grego *et al.* (2004) findings, we would suggest, quite logically, that cognitive processing speed was delayed due to the fatiguing influence of prolonged exercise. We might then speculate that inefficient increases in attentional resources were allocated to successfully execute task demands.

As such, two seemingly similar studies yielded disparate findings, which is understandable given the differences in the timing of the cognitive testing relative to the time of the intervention. Thus, the task now is to determine what logical generalizations can be made from these two studies. Given that both Yagi *et al.* (1999) and Grego *et al.* (2004) used similar stimulus discrimination tasks, the lack of consensus across studies is not readily apparent. It is possible that the P300 component fluctuates during exercise similar to that of other physiological measures and that the frequency of data collection (Grego *et al.*, 2004) was not sufficient to capture these changes. Examination of the early measurement period (i.e. minute 3) of Grego *et al.* (2004) provides minimal support for this speculation and supports the findings of Yagi *et al.* (1999). Specifically, P300 amplitude decreases by approximately 0.5 μV when measured 3 min following the initiation of the exercise intervention. The later measurement periods indicate increases in amplitude. Accordingly, it is possible that brief exercise interventions may decrease the P300 component amplitude, while longer interventions increase amplitude. Future research should follow up on this possibility, which would be necessary to draw strong inferences regarding the underlying meaning of such a finding. Further, the implementation of a task that is challenging enough to yield behavioural changes during exercise would further allow for reasonable inferences to be drawn regarding the influence of in-task exercise on cognition and the resulting effect on task performance.

To date only a single study has examined the relationship between acute in-task exercise and ERPs using a task that requires variable amounts of executive control. The Eriksen flanker task (Eriksen and Eriksen, 1974) has frequently been used to test an individual's ability to manage interference from task-irrelevant information in the stimulus environment (Miyake *et al.*, 2000). This task requires participants to discriminate between two letters that are flanked by an array of other letters that have different action schemas associated with them. Variable amounts of interference control are required based on the compatibility of the letters that flank the target stimulus. Congruent stimuli (e.g. HHHHH) elicit faster and more accurate responses, whereas incongruent stimuli (e.g. HHSHH) elicit increased error rate and decreased response speed (Eriksen and Schultz, 1979) because the latter condition results in greater response competition (Kramer *et al.*, 1994; Spencer and Coles, 1999). This task has been associated through neuroimaging research with a neural network involved in the executive control of attention that includes the ACC and lateral prefrontal cortex, and parietal cortex (Bush, Luu and Posner, 2000; Fan *et al.*, 2005).

Pontifex and Hillman (2007) used a modified flanker task (Hillman *et al.*, 2006a; Posthuma *et al.*, 2002) in which participants were required to attend to a centrally located arrow flanked by other arrows oriented either in the same (i.e. congruent: <<<<< or >>>>>) or in the opposite directions (i.e. incongruent: <<><< or >><>>). Pontifex and Hillman (2007) collected ERPs from 41 college-aged adults in counterbalanced conditions of rest and 6.5 min of steady-state exercise on a cycle ergometer at 60% of their maximum heart rate (HRmax) as determined

during a maximal exercise test. An increase in P300 amplitude was observed during exercise over frontal and bilateral electrode sites across both conditions of the flanker task relative to rest. Such a pattern of findings suggests an inefficiency of neuroelectric resources during stimulus engagement. Additionally, Pontifex and Hillman (2007) observed a global increase in P300 latency during exercise relative to rest, suggesting delays in stimulus evaluation and classification speed. However, Pontifex and Hillman (2007) also assessed changes in earlier ERP components that occur during acute exercise through the analysis of the N1, P2 and N2 ERP components. The N1 and P2 components relate to aspects of visual discrimination (Luck, 1995; Vogel and Luck, 2000) and selective attention (Talsma and Kok, 2001), respectively. The N2 component relates to response inhibition during tasks that elicit conflict (Ridderinkhof *et al.*, 2002), such as the incongruent condition of a flanker task (i.e. an increase in conflict is generated by the two response mappings as opposed to the single response mapping in the congruent condition).

With regard to the earlier ERP components, Pontifex and Hillman (2007) found a parietal reduction in N1 amplitude and increased P2 amplitude at frontal and central electrode sites, suggesting a decreased capability to visually discriminate stimuli, but an increase in selective attention during exercise. These results may seem contradictory, however Pontifex and Hillman (2007) suggested that the increase in P2 amplitude is indicative of the activation of an on-line, top-down cognitive control mechanism (as described above) to correct for deficits in stimulus engagement. Carter *et al.* (2000) further suggest that increases in top-down cognitive control would relate to reductions in response conflict leading to a reduced activation of the ACC (Colcombe *et al.*, 2004), which is thought to be the neural generator of the N2 component (van Veen and Carter, 2002). As such, additional support for this interpretation is provided through global reductions in N2 amplitude along with longer N2 latency, suggesting a reduced ability to inhibit inappropriate responses and delayed processing speed during exercise.

Taken in consideration with the P300 findings, Pontifex and Hillman (2007) suggested that the earlier ERP components index stimulus encoding deficits that occur during acute aerobic exercise leading to reduced quality of information processing and delays in cognitive processing speed; thus requiring an increased need to allocate attentional resources towards the task and upregulation of top-down cognitive control. Additionally, no ERP differences were observed between task conditions requiring variable amounts of executive control (i.e. congruent, incongruent), suggesting a more general shift in the underlying neuroelectric system that supports cognitive function during acute exercise.

Further support is garnered from the behavioural data, since participants exhibited reductions in response accuracy during exercise only in response to the incongruent condition, which requires increased interference control relative to the congruent condition. Taken together with the neuroelectric data, the findings suggest that in spite of deficits in stimulus acquisition and delays in cognitive processing, participants are still capable of responding quickly and accurately during exercise relative to rest during the congruent condition (low interference control requirement). That is, the

relative neuroelectric inefficiency observed on congruent trials during exercise did not influence task performance. However, the incongruent condition (high interference control requirement), which also exhibited neuroelectric inefficiency, did result in reductions in task performance during exercise, likely due to the inability to inhibit neural resources, resulting in a decrement in the ability to accurately discriminate between target and flanker stimuli or an inability to inhibit responses mapped to interfering stimuli, or both.

As the neuroelectric literature on the effects of acute, in-task, aerobic exercise is relatively sparse and conflicting, it is difficult to make broad generalizations regarding the nature of changes that occur during acute, aerobic exercise. However, it is clear that the P300 component exhibits changes across tasks that require relatively simple stimulus discrimination as well as tasks that require variable amounts of executive control. Although the assessment of ERPs during exercise was previously difficult (as even the slightest movements produced interference to the EEG signal), the advancement of various data collection techniques and sophisticated digital filters has led to a growing number of laboratories attempting to assess neuroelectric indices of cognition during exercise. As it is likely that this area will continue to grow, future research should attend more carefully to the design of the cognitive tasks employed in an effort to embrace a cognitive neuroscience perspective, utilizing tasks that target specific neural networks and structures to better make inferences regarding exercise effects on brain and cognition.

8.4 Event-related brain potentials following exercise

In contrast to the small literature base assessing neuroelectric changes in cognitive function during exercise, a relatively larger literature has investigated neuroelectric changes in cognitive function following acute exercise, with the majority of studies examining the P300 component. Further, many studies have opted to examine the P300 using versions of the oddball task (i.e. auditory and visual), which is described above. Other research has employed different (simple) stimulus discrimination tasks in which the participant receives an auditory warning stimulus (S1) followed by a second auditory (imperative) stimulus (S2) and they are instructed to respond to the latter stimulus (Kamijo *et al.*, 2004a). Finally, few studies have employed tasks requiring aspects of executive control (Hillman, Snook and Jerome, 2003; Kamijo *et al.*, 2004b; Themanson and Hillman, 2006). Although not all studies will be described in detail in this section, the interested reader may refer to Table 8.2 for a brief description of each.

Available evidence examining acute exercise effects on the P300 potential using an oddball task have again provided discrepant findings. That is, to the best of our knowledge, four published studies have examined acute aerobic exercise effects on the oddball-P300. Of these studies, two have observed no change in the P300 component as a function of an acute bout of exercise, while one has observed an increase in P300 amplitude and the other observed an increase in amplitude and

Table 8.2 Summary of findings of studies performed to assess the changes in neuroelectric indices of cognition following an acute bout of exercise.

Author(s)n	*n*	Time of test	Exercise intervention	Cognitive task	Result
Duzova *et al.* (2005)	31 college students (separated into high, moderate, and low physical activity levels)	Pre-test and post-test	Maximal exercise test	Auditory oddball task	No effects for P3. Increase in N2 amplitude following exercise at frontal sites for the high physically active group
Grego *et al.* (2004)	12 trained cyclists	Pre-test, 3 min, 36 min, 72 min, 108 min, 144 min, post, 15 min post	180 min cycling at approximately 66% of VO_2max	Auditory oddball task	No effect
Hillman, Snook, and Jerome (2003)	20 young adults	Baseline and post-test	30 min running on a treadmill at approximately 83.5% of HRmax	Modified flanker task	Increase in P3 amplitude following exercise relative to baseline Shorter P3 latency for incongruent trials following exercise relative to baseline
Kamijo *et al.* (2004a)	12 adults (22–33 yr)	Baseline and post-test	Approximately 18 min of cycling until volitional exhaustion (high intensity), at an RPE between 12 and 14 (medium intensity), and at an RPE between 7 and 9 (low intensity).	S1-S2 Reaction time task	Decrease in early and late CNV amplitudes following high intensity exercise. Increase in CNV amplitude following moderate intensity exercise.

(*continued*)

Table 8.2 (*Continued*)

Author(s)n	*n*	Time of test	Exercise intervention	Cognitive task	Result
Kamijo *et al.* (2004b)	12 adults (22–33 yr)	Baseline and post-test	Approximately 18 min of cycling until volitional exhaustion (high intensity), at an RPE between 12 and 14 (medium intensity), and at an RPE between 7 and 9 (low intensity).	Go/no-go task	Go: Increase in P3 amplitude at Frontal and Central regions following medium intensity Global reduction in P3 amplitude following high intensity exercise No-go: Global increase in P3 amplitude following medium intensity exercise Reduction in P3 amplitude at Central sites following high intensity exercise
Magnié *et al.* (2000)	20 college students (separated into high-fit and low-fit groups)	Pre-test and post-test	Cycling to exhaustion	Auditory oddball task	No effect for N1, P2, or N2. Global increase in P3 amplitude after exercise. Global reduction in P3 latency after exercise.

Nakamura *et al.* (1999)	7 adults (29–44 yr)	Pre-test and post-test	30 min of jogging at a comfortable and self selected pace	Auditory oddball task	Increase in P2 amplitude at frontal and central sites Increase in P3 amplitude at central and parietal sites No effect for N1 or N2 amplitude or for latency at any component
Themanson and Hillman (2006)	28 young adults (separated into higher-fit and lower-fit groups)	Baseline and post-test	30 min running on a treadmill at approximately 82.8% of HRmax.	Modified flanker task	No effect for ERN or Pe
Yagi *et al.* (1999)	24 college students	Pre-test, during, post	10 min cycling at a HR between 130 and 150 bpm.	Auditory and visual oddball tasks	No effect

decrease in P300 latency. Specifically, both Grego *et al.* (2004) and Yagi *et al.* (1999) observed that exercise was unrelated to modulation of the P300 component following the cessation of exercise. As described in the previous section, both observed changes during exercise, with conflicting results reported across the two studies. Despite the differences reported during exercise, both Grego *et al.* (2004) and Yagi *et al.* (1999) showed that P300 recovered from the acute bout of exercise such that the amplitude and latency did not differ from the pre-exercise baseline. Further, both data sets did not imply that repeated exposure to the task resulted in the nonsignificant findings from pre- to post-exercise, since P300 was modulated in such a manner that the latency increased during exercise (Yagi *et al.*, 1999) and then decreased following exercise to the point where it did not differ from the pre-exercise measurement. In other words, the pattern of findings indicated that cognitive processing speed was decayed during exercise, but recovered to the baseline level upon cessation of the exercise.

In the case of Grego *et al.* (2004), a nonsignificant increase in latency was observed following the acute bout, suggesting that although participants engaged in 3 hours of cycling, the P300 recovered rather quickly, since latency differences were not observed immediately and 15 min following the cessation of strenuous exercise. However, it should be noted that P300 latency was 85 ms slower following exercise relative to the pre-test measure, indicating that although significance was not achieved between test sessions, delays in cognitive processing speed were observed. This delay in P300 latency is not surprising given the nature of the exercise intervention. What is surprising is that the large difference from pre- to post-intervention (i.e. mean of 85 ms) did not achieve significance. Thus, the possibility remains that this nonsignificant finding may have been the result of the relatively small sample size employed. As such, future research should attempt to replicate these findings with a larger sample to better determine the exact nature of long-term exercise on cognitive processing speed. Nakamura *et al.* (1999) corroborated the above mentioned findings as P300 latency was unchanged in a small sample ($N = 7$) of individuals, who had completed a 30 min self-paced jog. Taken together, these data indicate that cognitive processing speed, as measured via P300 latency, is unrelated to acute aerobic exercise when assessed via an oddball task. However, limitations in the generalization of these findings remain due to the high variability observed in the P300 response and the small sample sizes across all three studies.

Given that the exercise interventions differed considerably across the three studies, one may begin to believe that no relation exists between acute exercise and P300 latency. However, Magnièe *et al.* (2000) also examined the P300 component to an oddball task following a maximal exercise test and observed a decrease in P300 latency and an increase in P300 amplitude following the acute bout, suggesting benefits to both cognitive processing speed and the allocation of attentional resources during stimulus encoding. These findings are in direct opposition to the earlier works and suggest that acute (and exhaustive) exercise is related to improvements in cognitive function through an increase in attentional resource allocation during the updating of working memory processes and faster cognitive processing

speed. Accordingly, the field has been unable to achieve consensus regarding whether the oddball-P300 is affected by an acute bout of aerobic exercise.

Several obvious reasons may account for these differences, including properties of the exercise intervention, properties of the oddball task used to elicit the ERP, time of testing relative to the cessation of exercise, small sample sizes and individual differences across the samples tested. The interested reader is referred to Kamijo (in press) for a discussion of these factors. Relevant to the direction of this chapter is the fact that the lack of consensus across studies may be due to the fact that this relatively simple oddball task engages a large neural network that is involved in the allocation and focusing of attention, the updating of working memory to changes in the stimulus environment and stimulus maintenance. The neural networks and structural generators that have been linked to these processes (and ultimately result in generation of the P300) include the frontal lobe, ACC, infero-temporal lobe, hippocampal formation and parietal cortex (Polich, 2004). That is, it is possible that differences in the various experimental protocols have led to differential findings because several specific brain regions are involved and it is not clear how exercise influences each of these specified regions. As such, the above mentioned findings have brought a certain degree of confusion regarding the relation of acute exercise to the P300 when elicited by the oddball task, and not much progress has been made in linking the changes in cognition to the supporting brain tissue. One issue that would bring clarity to these discrepant findings would be the use of a different task that was sufficiently difficult to modulate task performance. Thus, this additional information would provide a basis in which to better interpret the P300 findings, allowing for reasonable inferences to be drawn.

Accordingly, other research has examined the relationship between acute exercise and ERPs using tasks that elicit variable amounts of executive control, with the goal of linking neuroelectric changes with frontal lobe function, since executive processes have repeatedly been shown to be supported, in large part, by this region of the brain. Although ERPs are not ideal for measuring specific sources of activation due to their low spatial sensitivity, reasonable inferences can be drawn when neuroimaging findings (i.e. functional magnetic resonance imaging, dipole modelling) are considered. Hillman, Snook and Jerome (2003) used a flanker task (described above) to examine the relationship between a 30 min acute bout of moderately hard exercise and the P300 potential. Findings supported, in part, those of Magniè *et al.* (2000), as increased amplitude and decreased latency were observed. The interpretation of the findings differed in that Magnié *et al.* suggested that exercise increased central nervous system arousal, which related to a global increase in neuroelectric activation. Alternatively, Hillman, Snook and Jerome (2003) suggested that the findings, although general across conditions of the flanker task (i.e. increased P300 amplitude), were also selective to task conditions requiring greater amounts of interference control, since P300 latency decreased following acute exercise only during the incongruent condition. That is, the findings suggested that cognitive processing speed was increased only during task conditions requiring increased executive control. It is argued herein that the flanker task may be a superior means for

determining the relation between acute exercise and ERPs, since task conditions that elicit variable amounts of executive control are incorporated, allowing for greater comparison of the acute effects of exercise on cognitive processes involved in each task condition. In other words, the conclusion of a global increase in P300 following acute exercise may have been premature since only the target condition was compared prior to and after acute exercise. Through the comparison of multiple task conditions elicited by the flanker task, it appears that the sensitivity of cognitive processes to acute exercise changes with the amount of interference control required. Based on prior neuroimaging research (Colcombe *et al.*, 2004), we can begin to make inferences regarding the disproportionately larger effects of acute exercise on processes subserved by the neural networks that involve the frontal lobe.

Other research employing a different executive control task supports the notion that acute exercise may differentially influence executive control processes. Kamijo *et al.* (2004b) examined the P300 during a go/no-go task. The go condition is synonymous with an oddball task in that participants discriminate between two stimuli with varying probabilities and respond only to the target stimulus, which occurs during a minority of the trials. The no-go condition utilizes the same study parameters, but the participant is instructed to respond on the majority of the trials and withhold their response to the minority of the trials (i.e. the target stimulus in the go condition). This latter condition requires a greater amount of response inhibition since a prepotent response is created due to the high probability of the presentation of a stimulus requiring a response. Results from Kamijo and his colleagues indicated that both the go and no-go P300 amplitudes were increased following moderate exercise (the exercise condition most closely related to the exercise intervention in Hillman, Snook and Jerome, 2003). Although they did not compare the magnitude of the change across conditions, the mean data indicate a greater increase in the no-go condition, supporting the idea that tasks requiring greater amounts of executive control may be disproportionately influenced by acute exercise. Clearly, future research needs to directly test this hypothesis, but it should be noted that considerable evidence for the disproportionate relation of chronic exercise to changes in executive control functions have been reported across several studies (Hillman *et al.*, 2006a; Hillman, Castelli and Buck, 2005; see Colcombe and Kramer, 2003 for review).

Finally, several studies have examined other ERP components following acute exercise. Kamijo *et al.* (2004a) examined the early and late components of the contingent negative variation (CNV) and found that high intensity exercise reduced the amplitude of both components. Given that the early CNV is related to attentional orienting (Weerts and Lang, 1973) and the late CNV is related to motor preparation (van Boxtel and Brunia, 1994), this observed reduction following highly intense exercise suggests decrements in these aspects of cognition. Interestingly, low and moderate intensity exercise was unrelated to the modulation of the early and late components of the CNV. In addition, Themanson and Hillman (2006) examined the relationship between an acute bout of aerobic exercise and response-locked action monitoring processes by asking participants to exercise for 30 min on a treadmill at approximately 80% HRmax and then examining indices of self-regulatory action

monitoring (i.e. the error-related negativity [ERN] and the error positivity [Pe]) following acute exercise. The ERN and Pe are thought to relate to neural correlates of action monitoring and error awareness, respectively. Action monitoring processes are related to one's ability to monitor behavioural task performance and adapt performance in order to improve the quality of one's subsequent interactions with the environment. These processes are indexed with both neuroelectric and behavioural measures and have been found to be related to levels of cardiorespiratory fitness (Themanson and Hillman, 2006) as well as physical activity involvement (Themanson, Hillman and Curtin, 2006).

However, Themanson and Hillman (2006) observed no relationship between an acute bout of aerobic treadmill exercise and neuroelectric and behavioural measures of action monitoring (i.e. ERN, Pe, reaction time, response accuracy). Alternatively, an association was observed between levels of cardiorespiratory fitness and indices of action monitoring such that the higher-fit group exhibited a relative reduction (i.e. smaller ERN) in the conflict-related neuroelectric index of action monitoring associated with error responses and a relative increase in both neural and behavioural post-error adjustments in top-down attentional control (i.e. longer reaction time latency on the trial immediately following error commission). Thus, it was concluded that exercise may not produce a powerful enough influence on these cognitive processes when it is distributed in a single, acute bout, but repeated involvement in aerobic exercise leading to increases in cardiorespiratory fitness may be related to improvements in self-regulatory action monitoring processes.

8.5 Future directions and conclusions

There are several interesting and potentially valuable directions for future research that stand to increase cognitive health and effective functioning across individuals. Specifically, no research to date has employed neurocognitive measures to examine acute exercise effects on cognitive performance using samples of children, older adults or individuals with cognitive or physical diseases. This area of research clearly needs to receive attention as these populations may be disproportionately responsive to acute exercise interventions on cognitive performance. Studies of chronic exercise participation in both pre-adolescent children (Hillman, Castelli and Buck, 2005) and older adults (Hillman, Castelli and Buck, 2005) have supported the notion that exercise promotes better cognitive performance during the early and late stages of the human lifespan. These studies have further provided a basis from which to understand the specific cognitive processes that are influenced by exercise participation. Similarly, future research investigating acute exercise effects on cognition should employ these populations to determine whether they would be more amenable to intervention, which cognitive processes are affected and the duration of cognitive change.

However, future research efforts must also embrace a cognitive neuroscience perspective that utilizes specific tasks that are supported by specific neural networks. Much of the research to date has employed little rationale for why the particular tasks

were chosen or the relation between these tasks and their underlying neural networks. That is, the extant literature has not established a link between changes in cognition and the brain tissue supporting these changes. Further research efforts need to draw reasonable inferences through the selection of tasks that have been linked to specific brain tissue through prior neuroimaging research. The extant cognitive neuroscience literature has established many relationships related to both executive and nonexecutive functions. With this in mind, future research efforts should branch into the various other executive functions (i.e. response inhibition, working memory, mental flexibility) as there is a wealth of neuroimaging data available that provides a sound rationale for their examination through an understanding of the neural networks involved. As such, future research would be better able to translate basic laboratory findings to cognitive processes involved in every day life.

In conclusion, available data indicate that neuroelectric concomitants underlying various cognitive processes are influenced by acute exercise, but the body of literature is not as convincing as one might hope at this time. This is largely due to the competing results that have been observed across seemingly similar studies. One obvious distinction that has been observed in the literature is the deficits that emerge in both the neuroelectric profile and task performance during exercise relative to the observed improvements in task performance and changes in the neuroelectric profile that support task performance following acute exercise. This distinction illuminates the need for future efforts aimed at the timing of the various influences upon cognitive performance and the need to tie these influences to the underlying neural networks that are influenced by exercise. Finally, research into the acute effects of exercise on neurocognition remains an exciting area of study as findings allow for the increased understanding of how health factors influence specific processes underlying cognitive performance.

9

Exercise and decision-making in team games

Terry McMorris

Although much of the research into the effect of exercise on cognitive function has been carried out by sports scientists, very little has included direct reference to sport. In this chapter, we examine research carried out in our laboratory into the effect of acute exercise on decision-making in team games. All of the published studies have used football, or soccer as it is known in North America, tasks but we have also carried out unpublished work on decision-making in Rugby Union.

The importance of decision-making in team games cannot be overstated and the fact that decisions must be made during, and immediately following, exercise of differing intensities is self-evident. From the early work of Poulton (1957) to the present day, it has been accepted that skill in team games depends not only on technique, but also on decision-making. Technique refers to the ability to carry out the motor component, while skill is knowing which technique to use in any particular situation (Knapp, 1963). As a football coach at several different levels, I often came across players who were technically gifted, but consistently chose the wrong option. In deciding which young professionals should progress to the senior ranks I often found that their ability to make the correct decision was more important than technique or physical strengths.

Information processing theorists see decision-making in team games as requiring the player to accurately perceive the situation, hold what they perceive in short-term memory and compare the present situation with past experiences stored in long-term memory. As we saw in Chapter 2, this is the precise role of what Baddeley (1986) termed working memory. Positron emission tomography research has shown that working memory tasks stress the dorsolateral prefrontal cortex, anterior cingulate cortex, hippocampus and probably the basal ganglia and cerebellum (Artiges *et al.*, 2000; Jahanshahi *et al.*, 2000). Thus, such tasks are thought to be particularly

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susceptible to the negative effects of stress (Drevets *et al.*, 1995). However, they may also benefit from increases in arousal when exercise intensity is moderate (Pribram and McGuinness, 1975). It was with this in mind that I set out, in 1996, to examine the effect of acute exercise on decision-making in football. I chose football for practical reasons – my own expertise and experience; my contacts with top-class coaches, who could help devise the decision-making tests; and the availability of experienced players to act as participants. The results, however, readily apply to all team games and, indeed, to many individual games. My original hypotheses were that moderate intensity exercise would have a positive effect on decision-making and that maximal intensity exercise would have a negative effect.

I did not hypothesize an inverted-U effect. I felt that during maximal intensity exercise performance would be worse than that at rest and during moderate intensity exercise. I did not foresee a true catastrophe as might be expected by the proponents of catastrophe theory (Hardy, Parfitt and Pates, 1994), but more of what one might term an inverted-U effect. My theoretical underpinning was Kahneman (1973) allocation of resources theory. This is examined in some detail in Chapter 1, so I will simply outline it here. According to Kahneman, we have a limited number of resources but the amount increases as arousal rises. At low levels of arousal, we have few resources to allocate to a task. If we are highly motivated, we can apply all, or most, of the resources to the task. If the task is not too complex, performance can be as good as during moderate levels of arousal. At moderate levels of arousal resources increase and we can comparatively easily allocate these resources to the task. However, during high levels of arousal, even though resources increase further, we are not able to allocate resources to the task. This is, of course, similar to the arguments of Dietrich outlined in Chapter 3.

In the rest of this chapter, we will follow the research as it unfolded chronologically. Hopefully, I can overcome my own personal biases and critique the work honestly. In the final section, I outline the future research needed in this area and discuss the implications for players and coaches of team games.

9.1 Designing a decision-making test

The first problem I faced was to design a valid, reliable and objective football-specific decision-making test. Doing this was far from easy. I had developed a football-specific decision-making test previously (McMorris and MacGillivary, 1988), but wanted to improve on that test by making it more objective and easier to administer. I began by a thorough review of the football literature and the psychology literature into skilled performance, the decision-making aspects in particular. I also called on a group of very experienced coaches to help prepare the tests. The first stage was to highlight possible scenarios or situations that were common in football. These were firstly drawn diagrammatically (see Figure 9.1 for an example) and circulated to the coaches. I asked the coaches to isolate situations in which there was only one optimal

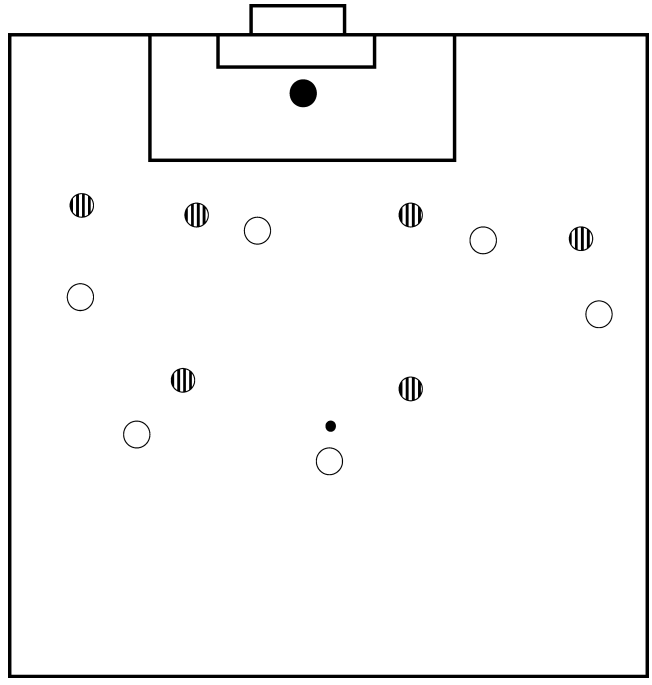

Figure 9.1 Example of a decision-making problem for the player in possession of the ball.

answer. Only those situations where all of the coaches agreed on the answer were included in the next stage.

The decision was to be made for the player in possession of the ball. In order to aid objectivity only four possible options were used, pass the ball, run with the ball (i.e. run forward into unopposed space), dribble (i.e. run forward, but going past a defender who would try to tackle) and shoot.

Stage 2 was to depict these situations not simply diagrammatically but in a more realistic manner. I did think about getting players to pose in the situations. However, the German sport psychologist Werner Kuhn had tried this and found that it was unsatisfactory (personal communication, 1988). Surprisingly, the main problem was that it looked unreal. I therefore decided to continue with the method I had used in 1988, that is make slides using model players. For reasons that an art expert might be better able to explain (impressionism, possibly), this method produced slides that looked more realistic than having real people pose. The model players (6.4 cm in height) were set up on half a standardized table tennis table (1.37 $\times$ 1.2 m). The table was marked out as half a football pitch using white tape. The areas were in proportion to a real football pitch on a scale of 2.4 cm to 0.91 m. Each situation contained a goalkeeper, four back defenders, two midfield defenders, two strikers and four midfield attackers. Colour slides were obtained with the camera positioned so that the view was from the centre of the halfway line.

Once the slides had been made, I carried out an initial screening and rejected those where it was obvious that the intended outcome had not been achieved. There is a difference between looking at something in plan or diagrammatic form and when photographed from a position that might induce parallax error. The rest were sent to the panel of coaches, after which several more were removed. I was left with 15 situations that were acceptable. However, a third stage was still required. As I wanted the participants to be tested at rest, and during moderate and maximal intensity exercise, I needed to create three sets of the test that did not differ significantly from one another. I took the 15 situations and attempted to produce three variations of each situation, for example the 'same' problem but set on the right, left and centre of the field. This proved to be much harder than I had anticipated and four situations had to be discarded. The test was returned to the coaches for final scrutiny. Next I had to statistically examine reliability, that is ascertain whether or not administering one set after the other would lead to a learning effect.

So far the coaches and I had been able to spend time viewing the slides before making a decision. In the test, I wanted to set a time limit for viewing each slide in order to make the task more realistic. Therefore, the slides were shown to the participants using a slide projector fitted with a tachistoscopic timer. Slides were shown for 2 s but participants were told that they were being tested for speed and accuracy, therefore they had to make a decision as quickly as possible and not wait until the picture disappeared. In order to examine speed a voice reaction timer was used. The timer began when the slide was displayed and was stopped when the participant spoke. Thus, there were two dependent variables, speed of decision and accuracy.

In order to statistically examine reliability, a group of individuals of similar football ability and experience to those that were to be used in the test undertook the three versions of the test one after the other. Order of presentation between participants was randomized. Initial results showed that one situation had to be eliminated in order to show a reliability coefficient that was satisfactory. In fact, the reliability coefficient of the final test, as determined by the intra-class test of reliability by analysis of variance, was very high ($R = 0.91$ for speed of decision and $R = 0.82$ for accuracy).

Ecological validity

This test can be criticized for a lack of ecological validity. Although a time constraint was included and the situations were adjudged by experts to be realistic (logical or face validity), one does not observe static displays in football. There is movement. We decided not to attempt, at this moment in time, to produce a dynamic test but to press ahead to establish whether or not exercise would have an effect on our static test of decision-making. As far as the sport was concerned, our aim was to establish a prima facie case for an effect of exercise on decision-making and then, at a later date, use a more ecologically valid test. We will return to this issue later in the chapter. Indeed the exercise protocol used also lacked ecological validity. Participants were tested at rest and while cycling on an ergometer at 70 and 100% maximum power output

($\dot{W}_{MAX}$). Obviously footballers do not use cycles. More importantly, from an ecological point of view, footballers carry out repeated, short-duration sprints rather than continuous work. As stated above, I was well aware of this at the time but was in the ecological validity versus experimental control situation. I opted for the latter and by using percentages of $\dot{W}_{MAX}$ could be confident about the amount of physiological stress placed on the participants. From a football point of view, validity is limited but from an exercise-cognitive function perspective there are no problems.

9.2 Research results

In the first experiment (McMorris and Graydon, 1997a [although this was, in fact, the first experiment, the paper was published later than McMorris and Graydon, 1996a and 1996b]), 15 university level footballers undertook the test at rest and during exercise at 70 and 100% $\dot{W}_{MAX}$. Repeated measures (RM) multivariate analysis of variance (MANOVA), with speed and accuracy of decision as the dependent variables, showed a significant effect for exercise. Observation of the separate univariate RM analyses of variance (ANOVAs) found that only speed significantly contributed to the results. Post hoc Tukey tests demonstrated that speed at rest was significantly different to that in the two exercise conditions, which did not differ significantly from one another. (Speed and accuracy were examined by RM MANOVA rather than separate RM ANOVAs as a speed–accuracy interaction may have been present.) This result was obviously a surprise to us. We had hypothesized an inverted-J but, in fact, performance during maximal intensity exercise was faster than in the other two conditions. We felt that drive theory (Hull, 1943) might present us with a plausible explanation for our data. According to Hull, increases in stress would lead to a linear improvement in performance if the task was well learned. We believed that the level of expertise and, in particular, experience of our participants may have accounted for the linear improvement. The fact that accuracy had not significantly contributed to the results also pointed to the task being well learned.

Thus, we felt that if we compared the effect of exercise on experienced footballers and nonfootballers we would get different results. If our conclusions regarding drive theory were correct, we would get a linear improvement in speed of decision and no effect on accuracy in the football players, but an inverted-J effect on both variables in the nonfootballers. In the second experiment (McMorris and Graydon, 1996a), we used the same protocol as in the first experiment but this time compared the effect of exercise on both experienced and inexperienced players. An interaction effect was shown but only speed of decision significantly contributed to the results. Moreover, the interaction effect was not as we had hypothesized. The post hoc Tukey tests showed that the experienced group's speed of decision at rest was significantly slower than in the two exercise conditions, which did not differ significantly from one another. There was no significant effect of exercise on performance for the inexperienced group. We argued that drive theory may also account for this as Hull (1943) stated that when a task is new, increased stress may well have no effect on

performance. We felt a little uneasy about such an explanation as the nonfootballers had, in fact, performed far better than we thought they would on the accuracy component of the task. Results were well above those expected by chance. This led us to examine two other possible explanations. The first was that our test was not as difficult as we had imagined and, secondly, that we had no control over the speed–accuracy trade-off as far as individual participants were concerned. This led to a further two experiments.

My own experience of coaching football had shown me that the biggest difference in decision-making skill between professionals and amateurs was more in 'off-the ball' situations than in 'on-the ball' scenarios, similar to those we had so far used. 'On-the ball' refers to decisions made by the player in possession of the ball, while 'off-the ball' refers to those decisions made by the other players. Thus, we (McMorris and Graydon, 1996b) decided to compare university footballers on the original 'on-the ball' test and on a new 'off-the ball' test. 'Off-the ball' situations can apply to defenders as well as attackers (offensive players). We decided to only look at attackers, as our panel of coaches felt that their decisions were the most difficult of all. The test was devised in the same way as the original test except that the player for whom the participant had to make a decision was marked by a white 'X' (see Figure 9.2 for a diagrammatical example). The participant had to state whether the 'player' should support the player in possession from behind by saying 'support'; run forward to receive a pass by saying 'run'; make a diagonal run to create space by saying 'diagonal'; or make a target to receive a forward pass by saying 'target'. Intra-class tests of reliability by ANOVA showed strong correlation coefficients, $R = 0.90$ for

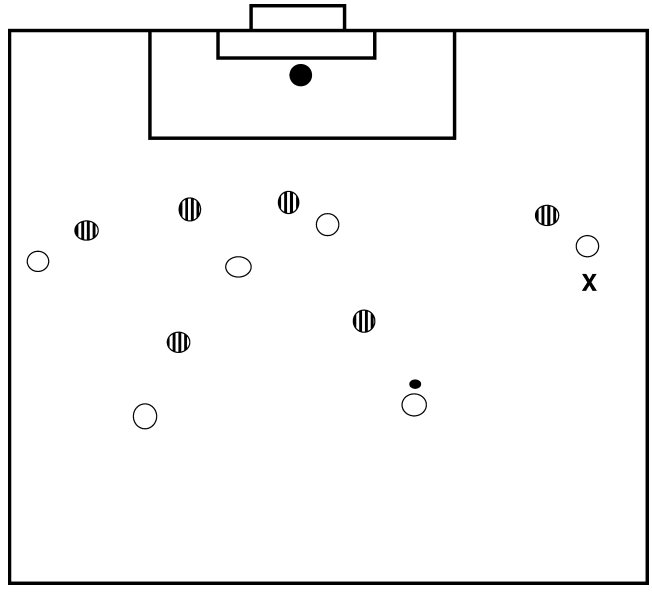

Figure 9.2 Example of a decision-making problem for a player not in possession of the ball. The player is marked with a 'X'.

speed of decision and $R = 0.72$ for accuracy. The same protocol as in the previous tests was used.

Results showed the expected between-task difference with the 'off-the ball' situations being far poorer, with both speed and accuracy contributing significantly to the results. There was, however, no interaction effect but a main effect for exercise intensity with improved speed and no effect on accuracy. Post hoc Tukey tests showed a significant linear improvement in speed from rest to that during maximal intensity exercise. These data most definitely cast major doubts on our previous explanations for the results. The results for accuracy show that the 'off-the ball' task was not easy or familiar but we still had a significant linear improvement in speed of performance. Thus, we turned to our hypothesis that speed–accuracy trade-off may be the cause for our 'strange' results.

In order to examine the speed–accuracy problem, we (McMorris and Graydon, 1996b) carried out a second experiment in which we divided university footballers of very similar experience into two groups. Group 1 were given the 'off-the ball' test in exactly the same way as in the previous experiment. Group 2 were presented the test in the same way except that they were told that speed was not being examined, only accuracy. In fact, both were measured. Results showed that Group 2 were much slower than Group 1, as one would expect, but there was no significant difference in accuracy. Most surprisingly there was no exercise $\times$ condition interaction effect, but there was again a significant main effect for exercise. Post hoc Tukey tests showed that speed during maximal intensity exercise was significantly faster than that at rest. Thus, we had to turn to some other explanation for our findings.

Although I had not been unduly concerned about the ecological validity of the decision-making test, I realised that I was making certain assumptions with regard to the similarities between decision-making in a game and in our test. In a game the player is constantly following play. He/she knows where the ball is at all times. In our test that was not the case. When the slide was presented the first task for the participant was to search for the ball. Only when this had been completed could the participant begin to make a decision. Given that according to Humphreys and Revelle (1984), simple tasks like visual search can be facilitated by high levels of arousal, I thought that this may well be what was happening in our tests, rather than speed of decision per se being affected. Therefore, we (McMorris and Graydon, 1997b) had participants undertake a speed of visual search task.

Slides of typical football situations similar to those used in the previous experiments were designed. Three sets of 15 slides were made, with 10 slides in each set containing a ball and 5 without a ball, that is the players were positioned as in a game but the ball was not included. This was necessary to make sure that the players had actually searched for the ball. Participants had simply to search the display as quickly as possible and to state whether the ball was present or absent. In order to examine whether or not the exercise affected visual search generally or only in structured game-type situations, a similar test was devised using unstructured, nongame situations, that is the players standing around in groups but not in relation to playing football. The test was examined for reliability and very high coefficients for

the game and nongame tests were found, $R = 0.94$ and 0.92 respectively. Performance was again tested at rest and during exercise at 70 and 100% $\dot{W}_{MAX}$. A structure × exercise intensity RM ANOVA showed a main effect for exercise intensity. Post hoc Tukey tests found that speed during maximal intensity exercise was significantly faster than in the other two conditions.

Given the results from the visual search test, I was confident that we had found the answer. As we had shown an improvement in speed of search in, not only, a game-type situation but also in a nongame situation, it appeared very much as though our previous results had been due to improved exercise-induced speed of search rather than increased speed of decision per se. Humphreys and Revelle (1984) believed that simple tasks, such as visual search, would be facilitated by increases in arousal. However, the possibility that when we combined visual search and decision-making we might get different results had to be considered. If an individual is simply undertaking a visual search task they are not activating the same parts of the brain as when simultaneously undertaking a decision-making task; so further experimentation was necessary.

A second experiment (McMorris and Graydon, 1997b) was set up whereby experienced soccer players undertook the 'on-the ball' decision-making test at rest and during exercise at 70 and 100% $\dot{W}_{MAX}$. However, we not only measured accuracy and time taken from illumination of the slide to making a decision (total decision time) as in the earlier studies, but we also examined the time it took to perceive the ball (speed of visual search) and the time it took from spotting the ball to making the decision (speed of decision following ball detection). In order to be sure that participants were actually spotting the ball, we had a number of slides in which no ball was present. We did not record the time taken to decide that no ball was present. The results were surprising to us. RM MANOVA showed a significant effect of exercise but follow-up separate univariate RM ANOVAs demonstrated that only total speed of decision, speed of decision following ball detection and accuracy of decision contributed significantly to the results. Speed of visual search did not. That speed of visual search failed to demonstrate the same results as in the previous speed of visual search experiment suggests that including the decision-making aspect probably changes the nature of the information processing that the individual is undertaking. Given that total speed of decision and speed of decision following ball detection both significantly contributed to the results suggests that during visual search, the individual is actively assessing the positions of the players – both attackers and defenders – and holding this information in short-term memory. Once the ball is spotted the person can quickly make a decision. The most surprising result was the fact that accuracy improved albeit slightly during exercise at $\dot{W}_{MAX}$. Given the results of previous experiments this is difficult to explain. Effect size was high ($\eta^2 = 0.28$) but power at 5% was moderate (0.67).

Following these results we could only conclude that stress, in the form of acute exercise, had a beneficial effect on speed of decision-making in football, when carried out by experienced players. This was contrary to what inverted-U theorists would have expected and meant that we would have to reappraise the nature of decision-

making in football, in particular questioning the level of difficulty. Either drive theory presented the best explanation for our data or the task was not as complex as we thought. We had, however, a more pressing problem, namely the lack of consistency over all of the experiments with regard to the results for the effect of moderate intensity exercise on speed of decision. In some experiments moderate intensity exercise resulted in improved performance compared to at rest, in others it did not. Similarly, there was inconsistency when comparing performance during moderate and maximal intensity exercise. We had chosen 70% $\dot{W}_{MAX}$ as the criterion for moderate intensity exercise as this was considered to be an exercise intensity above the adrenaline and noradrenaline thresholds, that is the points at which plasma adrenaline and noradrenaline concentrations begin to rise exponentially (Mazzeo and Marshall, 1989; Podolin, Munger and Mazzeo, 1991). However, some authors had noted quite large differences in individuals' threshold levels (Schneider, McGuiggan and Kamimori, 1992; McMorris *et al.*, 2000). Therefore, we decided to carry out a test in which we examined footballers' decision-making skills at rest, during exercise at $\dot{W}_{MAX}$ and during exercise at each individuals' adrenaline threshold (T_A) (McMorris *et al.*, 1999). Chmura, Nazar and Kaciuba-Uscilko (1994) had shown the T_A and the noradrenaline threshold (T_{NA}) to induce improved reaction time and Cooper (1973) had claimed that it was exercise-induced increased concentrations of adrenaline and noradrenaline that caused improved cognitive functioning during moderate intensity exercise (see Chapter 2 for a detailed discussion).

Results for accuracy showed no significant effect, suggesting that the results of the previous experiment for this variable were something of an anomaly. Speed of decision at rest was significantly different to that at T_A and during $\dot{W}_{MAX}$. Thus, we concluded that T_A represented a point at which a significant improvement was shown. We decided that the ambiguities in our previous results were due to the failure to take into account inter-individual differences in percentage of $\dot{W}_{MAX}$ that would induce T_A and T_{NA}.

At the time we were certain that T_A and/or T_{NA} were the key factors in inducing increased speed of decision. However, research examining the effect of moderate exercise on other cognitive tasks showed that exercise intensities below T_A and/or T_{NA} can also induce improved performance (Allard *et al.*, 1989; Delignières, Brisswalter and Legros, 1994; Davranche *et al.*, 2005), thus suggesting that this assumption may be incorrect.

Decision-making times in our experiments show a linear trend in improvement from rest to maximal intensity exercise. However, we do not consistently see a significant difference between moderate intensity and either of the other two conditions. This lack of consistency may be due to the statistical treatment. The use of Tukey tests as the post hoc tests may have been inappropriate (see Tversky and Kahneman, 1971 for a discussion of the problems of using tests designed for large sample sizes with small numbers). The use of polynomial contrasts may have been better. Unfortunately I do not still have the raw data to carry out such tests a posteriori. It would appear that it may not be necessary to reach T_A and/or T_{NA} for an improvement to be seen.

At this stage, we felt that we had provided sufficient evidence to suggest that exercise actually improved speed of decision-making in team games but only in nonecologically valid laboratory tests. In order to increase, albeit slightly, the ecological validity, we carried out a decision-making test that required a psychomotor motor response (McMorris *et al.*, 2000). Experienced soccer players were shown a video of three attackers, each marked by a defender. The attackers were on the right, centre and left of a screen, which allowed life size representations of the players to be shown. On a signal, the attackers attempted to get free from their marker. Only one attacker was successful each time. The participants had to decide which attacker had freed himself, as quickly and accurately as possible. Once they made a decision they had to say right, left or centre and their voice reaction time was measured. Whole-body reaction time was also measured. In order to do this, participants stood on a reaction timer pad. As they made a decision they had to step off the pad; this measured the time. Once off the pad they had to kick a ball at a 30×24 cm target. Absolute, constant and variable errors were the dependent variables on the kicking aspect of the task. Participants were tested at rest and following exercise on a cycle ergometer at T_A and $\dot{W}_{MAX}$. There were no significant effects for any of the variables. With regard to the reaction time variables, we concluded that the way in which the participants undertook the test may have affected results. There was a time gap between dismounting the cycle ergometer and the beginning of the skill test. Moreover, the test itself took time and heart rates post-skill test compared to pre-skill test suggest that participants were not at the physiological arousal level for which we had aimed. Moreover, the nature of the test was not as we had hoped.

Our aim was to set a task that required the making of a decision. However, all the participant had to do was to observe which attacker freed himself and then make a pre-determined response. This is more a response time test than a decision-making one. It is likely that it is so simple that a ceiling effect was demonstrated. In this paper, we also questioned whether or not the tests used in our previous research had actually done what we had expected. Theoretically, making decisions in football requires the player to accurately perceive the present display; hold this information in short-term memory; compare the held information to similar past experiences recalled from long-term memory; and, from this comparison, make a decision. Thus, it is a working memory task activating the visuospatial sketchpad and the central executive. However, we failed to take into account the fact that for experienced footballers, this task would be well-learned. Thus, it would not activate the prefrontal cortex as much as we expected.

Summary

Our research suggests that accuracy of decision-making in football-specific tests is not affected by exercise. However, speed of decision appears to decrease as exercise intensity increases. More research is required using ecologically valid exercise protocols and psychomotor responses. We should not, however, overlook

a possible problem with the protocol. As Tomporowski (2003b) pointed out, there were only 10 situations per set of trials, This is very small and may not be sufficient to show any real effect.

9.3 Ecological validity and future research

The main aim of our studies was to determine a prima facie case for exercise having an effect on decision-making in team games, in particular football. At no time did I see the studies as being strong in ecological validity. The decision-making tests had some ecological validity. The test consisted of typical situations found in real football games and demanded an accurate and quick decision. However, the situations were static in nature, which is obviously not the case in football. Team games players see the situation developing before their eyes, they do not have to make a sudden instant decision. Moreover, the decision made by the player needs to be much more precise than that made by the participants in our experiments. The player must not only decide to pass the ball but must decide to whom to pass, when to pass, whether the pass is to feet or in front of the receiver, how hard to pass, to pass on the ground or in the air and so on.

Another important factor in decision-making in team games is that the player must make a motor response rather than a verbal one. If we take an information processing theory approach and assume that perception and decision precede action, we might expect the preparation of the motor response to have little or no effect on the quality and speed of the decision. However, according to Welford (1968), perception, decision-making and efferent organization take place simultaneously, so one might expect different results when the response is motoric in nature. McMorris *et al.* (2005a) found that in a test requiring a whole-body, motoric response to a three-choice response time task, exercise induced an inverted-U effect rather than the linear improvement demonstrated by research when the response required only a finger press. In a series of other experiments examining the effect of exercise on choice response time, when the response required an arm movement, no significant effect on the cognitive component was shown, although speed of movement improved (McMorris *et al.* 2003, 2005b).

With this in mind, one of my students, Ian Davies, a highly qualified Rugby Union coach, undertook an experiment using actual responses to game situations in rugby. Ian and Tony Weaden, a colleague at Chichester and also a highly qualified rugby coach, developed a series of situations in which the participant was given the ball and two team mates and had to beat three defenders. The defenders were briefed to behave in different but pre-determined ways, thus forcing the participant to make different decisions if he were to be successful. This test was carried out following rest and moderate (70% estimated maximum heart rate) and heavy exercise (90% estimated maximum heart rate). Results demonstrated an inverted-U effect. Some caution needs to be taken in interpreting these results, as the dependent variable, with regard to accuracy of decision, was made by subjective assessment by three experienced

rugby coaches. Although they were experts, there is a lack of objectivity. One must also assume that the collaborating players behaved similarly during each trial, which of course cannot be guaranteed. Nevertheless, I think that this experiment supports the idea that the decision plus action response may produce different results to the decision only response.

Another interesting factor in this study was the nature of the physical exercise undertaken. Ian undertook a comprehensive review of the literature concerning physical activity during a rugby game and, based on his findings, designed a rugby-specific physical circuit. Participants carried out this circuit, which included many of the aspects of rugby, for example sprinting, jogging, tackling, working against inertia and so on. Jens Bangsbǿ (1993) has developed a similar circuit for football. The weakness of the protocol was that only % of estimated maximum heart rate was measured as an indicator of exercise intensity, thus one cannot have any great faith in the control of the actual intensity.

In our experiments, we chose to have control over the power output of the participants. This meant that we could be more stringent in our experimental control but were not ecologically valid. The type of exercise we used is aerobic; however the type of exercise in football and other team games is different. Team games generally require short, fast bursts of speed, which stress the adenosinetriphosphate phosphocreatine (ATP-PC) system. This system relies on the phosphorylation of adensosinediphosphate to ATP. This process is dependent on the presence of phosphocreatine stored in muscles. This store is readily available but depleted very quickly. It lasts for about 10 s in the average person, but a trained athlete can draw on these stores for a much as 30 s. Replenishment of phosphocreatine can only take place following cessation of exercise. In many modern team games the anaerobic glycolytic system, which produces ATP without oxygen, is called upon. This system is only efficient for ~90 s. After that the individual must slow down and allow the re-synthesis of ATP by the aerobic system (see McMorris and Hale, 2006, for more detail).

Whether or not these types of activity will induce changes in brain concentrations of catecholamines is very contentious. As we saw in Chapter 2, there is evidence from animal studies and a strong theoretical basis (sympathoadrenal system activation) for aerobically induced increases in plasma catecholamines affecting brain concentrations. The case with regard to the ATP-PC and anaerobic glycolytic pathways may be different. I am not aware of any research examining the effect of very short-duration (< 30 s) exercise on plasma catecholamines concentrations. Research examining cycling at between 2 and 3 min (Strobel *et al.*, 1999; Bracken, Linnane and Broks, 2005) showed high concentrations of plasma catecholamines concentrations immediately post-exercise. Winter *et al.* (2007) found that repeated intermittent short-duration sprints (~2 min) resulted in significant increases in plasma catecholamines concentrations. It is logical to expect that the sympathoadrenal system reacts similarly to the ATP-PC and anaerobic glycolytic systems as it does with the aerobic system. Therefore, one would expect a similar effect on catecholamines concentrations in the brain to that induced by aerobic exercise. Moreover, Winter *et al.* showed a significant effect of undertaking short-duration sprints on the learning of complex

cognitive skills. Ian Davies work also suggests a significant effect on decision-making of game-type activities, which stress mainly the ATP-PC system but also invoke the use of the anaerobic glycolytic and aerobic systems. Interestingly, work carried out on the effect of game-type activities on the performance of motor skills has also shown significant effects (McGregor *et al.*, 1999; Davey, Thorpe and Wiliams, 2002).

Ecological Validity of Decision-Making Tests

When coaches attempt to assess the decision-making ability of their players they simply observe them playing. While this obviously has major limitations in that it is very subjective, high correlations ($r = 0.75$) between such observations and performance on objective tests of decision-making have been shown (McMorris and MacGillivary, 1988). Safrit (1973) claimed that this method was valid only if the 'experts' were truly expert and were given guidelines on which to base their judgments. She further advised the use of more than one expert and to include an examination of inter-rater reliability. Although the claims of Safrit are similar to those found in other research methods texts they have been repudiated by Franks and colleagues (Franks, Goodman and Miller, 1983; Franks and Goodman, 1986). Even those who accept expert judgments are concerned by subjectivity and so for several years now researchers have tried to design tests of decision-making that are valid, reliable and objective.

The use of tachistoscopically presented tests, as used by McMorris and Graydon (1996a, 1996b), were first designed by Bard and Fleury (1976) and further developed by Thiffault (1980). I have outlined the weaknesses of these tests above, with the main problem being their static nature. The first to attempt to introduce movement to such tests were the Belgian researchers Helsen and Pauwels (1988). These authors videotaped football games from the 1986 European and World Cups. They had confederates reproduce selected moves but with a camera 'replacing' one of the players. At a chosen time the ball would be passed to the 'camera'. At this moment the film would be stopped and participants had to make a decision as to what action the 'camera player' should take. The film was played on a 10×4 m screen, which allowed representations of the players and the field to be realistic in size. Helsen and Pauwels also improved ecological validity with regard to the response. Rather than have participants simply say what they would do, they had them make a motor response.

Helsen and Pauwels (1988) opened up a new method of dynamic tests and were followed by several researchers, most notably Mark Williams and colleagues (e.g. Williams and Davids, 1998; Vaeyens, Lenoir and Williams, 2007). These tests included the use of eye-mark recorders to determine the visual scan paths and amount of time spent fixated on different information in the display. Given our results for speed of visual search (McMorris and Graydon, 1997a), the effect of exercise on this variable is a possible avenue for future research. The obvious next stage for such tests is to use virtual reality.

9.4 Implications for team games players and coaches

If players are more efficient at decision-making when physiologically aroused, the need to warm-up before games is obvious. How intense this warm-up needs to be is somewhat contentious. One could argue that it must be above the T_A and T_{NA}, in line with the research of Chmura, Nazar and Kaciuba-Uscilko (1994) and McMorris *et al.* (1999). However, more recent research suggests that this is not necessary and exercise at as low an intensity as 50% $\dot{W}_{MAX}$ is adequate (Davranche *et al.*,(2005a, 2006b). In most team games, warm-up has been considered to be necessary as a means of limiting injuries, a rather dubious claim. It has, therefore, often been carried out somewhat half-heartedly by players, but I believe that if performers understand that it will help them play better they will apply themselves more readily. In my own coaching, I found a different attitude to warm-up once the possible benefits to decision-making had been explained to the players.

The second major implication for coaches and players depends on whether or not you accept that very high levels of physiological stress can and do result in a deterioration in decision-making, as found by Davies. If this is the case, practising while highly physiologically stressed may help. The former Director of Coaching for The (English) Football Association, Allen Wade, recommended this as far back as 1967 (Wade, 1967). The theoretical underpinning for Wade's recommendation is that exposure to the stressor can alleviate its potency. Therefore, practising while under stress may well have a beneficial effect.

10

Blood glucose and brain metabolism in exercise

Niels H. Secher, Thomas Seifert, Henning B. Nielsen and Bjørn Quistorff

For trained individuals, exercise is limited by provision of energy to working skeletal muscles, as illustrated by results in international athletic competitions. According to A. V. Hill, World records for running distances spanning from 100 m to a marathon can be formulated to reflect that the energy requirement is covered by a substrate store supplemented by a continuous provision of substrate and that idea is confirmed in follow-up studies on World records for running (Lloyd, 1966; Péronnet and Thibault, 1989) and for comparison of results in international rowing championships (Secher and Vaage, 1983).

Carbohydrate and phosphocreatine (PCr), but not fat energy stores, may be associated with the athlete's anaerobic capacity, while a continuous delivery of energy may be taken to represent the increase in metabolism measured as the pulmonary oxygen uptake. With calculation of human performance based on Hill's idea, results are predicted that deviate less than 1% from those observed in competitions, but the calculation is confined to the time for which a maximal effort can be maintained. During prolonged exercise, performance may be limited not only by the rate of pulmonary oxygen uptake, but also by the substrate available for oxygenation within skeletal muscles. During a marathon, the speed of running decreases markedly when the amount of glycogen is reduced significantly below 120 mmol glycosyl units kg^{-1} (Karlsson and Saltin, 1971). Muscle glycogen depletion is confined to the slow twitch fibres within the active muscles (Gollnick *et al.*, 1973), meaning that the glycogen concentration in the relevant fibres is low. In preparation for prolonged exercise, it is important that carbohydrate-rich meals secure an adequate energy store or muscle glycogen content that is further enhanced by so-called super-compensation following a previous bout of exercise that in itself reduces the muscle glycogen level markedly (Bergström and Hultman 1966; Bergström *et al.*, 1967).

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While glycogen depletion of skeletal muscles is relevant to exercise lasting for more than an hour, the level of blood glucose and, therefore, provision of glucose to the brain becomes critical when physical activity lasts for several hours or a day and even for exercise of shorter duration when no food is available.

Soft drinks are available at various stations along distance running, skiing and cycling competitions making it unlikely that the speed of locomotion becomes limited by the level of muscle glycogen or the ability of the liver to maintain blood glucose. The result may be predicted according to what may be considered Hill's axiom for exercise physiology, although based on cross-sectional rather than paired observations. Yet, both energy delivery and water balance is a concern when exercise is carried out outside a planned event. Notably, provision of energy is critical during tracking or cross country skiing. Moreover, in a cold environment, it is of utmost importance to maintain an elevated energy metabolism in order to withstand the challenge of the weather. This needs to be balanced with the insulation secured by clothing. It is a concern that weather conditions may change rapidly, not only for the duration of the planned trip, but also for the adequacy of the clothing. It is a further concern that if mountaineering is carried out at an extremely high altitude, as in the Himalayas, oxygenation of the neurones is affected and the subject becomes ill prepared for taking rational decisions in an often critical situation.

This chapter describes the cerebral metabolic response to exercise in regard to the effect of a reduced blood glucose level provoked by prolonged exercise. It also addresses how cerebral metabolism is affected by hypoxia, while an acute reduction in the blood glucose level in response to diabetes mellitus is mentioned briefly.

10.1 Cerebral metabolism during exercise

Traditionally, assessment of brain metabolism is based on a determination of cerebral blood flow (CBF) and relevant arterio-venous differences. With the Kety–Schmidt approach, there is no consistent change in CBF during exercise and, accordingly, there is no change in the cerebral metabolic rate for oxygen ($CMRO_2$) (Ide and Secher, 2000), in that only deep sleep (Madsen *et al.*, 1991) and anaesthesia are associated with a decrease. This stability of CBF and $CMRO_2$ in awake humans is in sharp contrast to what is reported during cerebral activation with evaluation of the regional CBF (rCBF) and metabolism, as evaluated by radioactive isotopes introduced by Lassen and Munck (1955) and reviewed by Lassen (1982). For these evaluations of the brain, there is a distinct increase in both blood flow and metabolism corresponding to the activated areas and, in fact, the demonstration of these increases has become synonymous with cerebral activation during evaluation of the brain by single photon tomography (SPEC), positron emission tomography (PET) and functional magnetic resonance imaging (fMRI). For exercise, it is also important that a motor task, for example the use of one hand, is associated with an increase in rCBF, as demonstrated by Olesen (1971) and confirmed in numerous follow-up studies including that by Orgogozo and Larsen (1979). Also with the less

elaborate apparatus required for near infrared spectroscopy (NIRS) of the brain, based on the same physical principle as fMRI in evaluating the ratio between oxyhaemoglobin and haemoglobin, activation including exercise is associated with an increase in CBF (Ide, Horn and Secher, 1999a).

Further support for a dynamic response of CBF to exercise is the finding that as determined by ^{133}Xenon clearance, CBF increases during dynamic exercise (Thomas *et al.*, 1989) and that is the case also for a transcranial Doppler evaluation of mean flow velocity (*V*mean) in the large basal cerebral arteries (Jørgensen, Perko and Secher, 1992a; Jørgensen *et al.*, 1992b). It has, however, remained a concern for evaluating cerebral perfusion by transcranial Doppler as to whether the diameter of the basal cerebral arteries remains stable during exercise. If sympathetic activation during exercise elicits vasoconstriction in basal cerebral arteries, an increase in *V*mean could represent a compensation for a reduced vessel diameter to maintain flow. However, during exercise, the increase in *V*mean for the middle cerebral artery (MCA) is in parallel with that in the 'initial slope index' of the ^{133}Xenon clearance-determined CBF (see Figure 10.1) (Jørgensen, Perko and Secher, 1992a) and the flow of the internal carotid artery (Hellström *et al.*, 1996; Huang *et al.*, 1991, 1992). Thus, the diameter of the large cerebral arteries does not change significantly during exercise and regulation of CBF takes place in the smaller arteries, as confirmed during neurosurgery (Giller *et al.*, 1993). For the noninvasive evaluation of CBF by *V*mean in basal cerebral arteries, it may be secured that changes are followed by a, at least quantitatively, similar change in the NIRS-determined cerebral oxygenation. Thus, if *V*mean and the NIRS signal change in parallel, it is difficult not to accept that CBF is also changed in

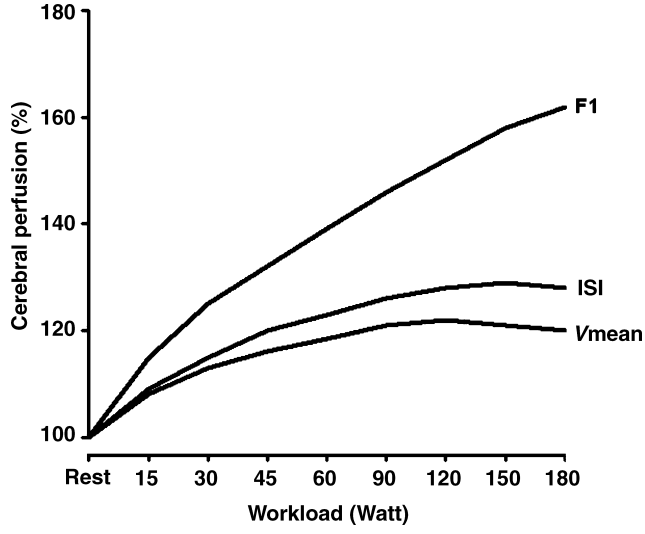

Figure 10.1 Parallel changes in middle cerebral artery flow velocity (MCA *V*mean) and the ^{133}Xenon clearance-determined initial slope index (ISI) of cerebral blood flow at various levels of dynamic exercise. Fast-compartment flow (F1) is considered to represent grey matter flow. Values are expressed relative to rest. (Modified from Jørgensen, Perko and Secher, 1992a.)

that direction, and that hypothesis is confirmed by clinical evaluations (Van Lieshout *et al.*, 2003). Also, it remains clear that *V*mean in basal cerebral arteries reports the regional distribution of flow during exercise. During right-hand grip exercise, MCA *V*mean increases only for the contralateral side (Jørgensen *et al.*, 1993a), while movement of one foot is associated with an increase in the contralateral anterior cerebral artery *V*mean, and only cycling is associated with a bilateral increase in MCA and anterior cerebral artery *V*mean (Linkis *et al.*, 1995). If flow velocity in basal cerebral arteries were a compensation for sympathetic vasoconstriction of these arteries, it would be likely that the response would be equal among the different branches of the internal carotid artery.

Together these various inflow evaluations of CBF during exercise indicate a dynamic aspect of CBF not reported with a concomitant determination of CBF and $CMRO_2$ using the Kety–Smith method of $\sim$45 mg 100 ml^{-1} min^{-1} (Madsen *et al.*, 1993). The most likely reason for the discrepancy between the stability of CBF during dynamic exercise evaluated as venous outflow from the brain and those methods appreciating the arterial inflow to the brain, is that the internal jugular vein used for the Kety–Schmidt method collapses when upright (Dawson *et al.*, 2004). In the upright position applied for exercise studies, venous drainage from the brain becomes dependent on spinal veins (Valdueza, von Münster and Hoffman, 2000) and if the stability of flow in the internal jugular vein was representative of the venous flow from the brain, exercise is associated with a consistent $\sim$25% increase in flow rate to the brain (50% when grey matter flow is evaluated: F1 in Figure 10.1) (Thomas *et al.*, 1989; Jørgensen, Perko and Secher, 1992a; Jørgensen *et al.*, 1992b) at the same time as no increase in its outflow. Yet, the total outflow from the brain is not measured during exercise and it needs to be determined whether the jugular outflow from the brain is enhanced during supine exercise when its relative contribution to flow would be expected to remain unaffected. A further complication for evaluation of the results obtained with the Kety–Schmidt method for CBF is that the venous drainage from the brain is not symmetric.

The hemispheres are drained by the larger right internal jugular vein, while the smaller left vein drains deeper structures of the brain of importance for evaluation of metabolism. For example, there is selective enhanced noradrenaline spill-over from deep structures of the brain in patients with arterial hypertension (Ferrier *et al.*, 1993).

The right internal jugular vein is used regularly for the Kety–Schmidt method and it would, accordingly, be expected that the measured variables are dominated by blood draining the hemispheres. The venous drainage from the brain is, however, not consistent and for some individuals, it is the left internal jugular vein that is the largest and accordingly drains the hemispheres. For a detailed evaluation of CBF based on the Kety–Schmidt method, the venous drainage to the two internal jugular veins needs to be evaluated, for example by labelling of the red cells by technetium and following their passage through the brain with a gamma camera (Ide and Secher, 2000), or the venous outflow from the brain could be evaluated indirectly by determination of the diameter of the vein on the two sides of the neck from an ultrasound image.

If CBF does increase during exercise, it is relevant which variables may drive the enhanced flow. In the era of the Kety–Schmidt method, regulation of CBF was a discussion dominated by its carbon dioxide reactivity and cerebral autoregulation, and both mechanisms are relevant to exercise because of the marked changes in mean arterial pressure (MAP) and the arterial carbon dioxide tension ($PaCO_2$). It may be added that although the established increase in rCBF, with cerebral activation, indicates a coupling between flow and neuronal activity, other influences need to be addressed.

The influence of $PaCO_2$ on CBF during exercise is important because moderate exercise is associated with a small increase in $PaCO_2$ that supports the increase in CBF and MCA *V*mean (Jørgensen, Perko and Secher, 1992a). On the other hand, intense exercise is associated with a reduction in $PaCO_2$, as ventilation increases exponentially with work rate. Accordingly, intense exercise is accomplished despite a decreasing MCA *V*mean (Linkis *et al.*, 1995; Rasmussen *et al.*, 2006), of consequence for oxygenation of the brain. Cerebral oxygenation is especially problematic during intense whole-body exercise because the arterial oxygen tension (PaO_2) decreases as the diffusion capacity of the lungs is reached and also because of the pronounced decrease in pH to a record low value of 6.74 during maximal ergometer rowing (Nielsen, 1999). With a concomitant reduction in PaO_2 and pH, in accordance with the Bohr effect on the oxyhemoglobin dissociation curve, the arterial oxygen saturation decreases from a resting value of 97 to 90% or even lower, and the combined effect of a reduction in CBF and arterial de-saturation makes the NIRS-determined cerebral oxygenation decrease by ~10% (Nielsen *et al.*, 1999). Such a decrease in cerebral oxygenation is not trivial in that only a slightly larger decrease is established during the loss of consciousness associated with a vasovagal syncope (Madsen and Secher, 1999). Similarly, cerebral oxygenation is challenged by the marked increase in ventilation provoked by exposure to cold water (Mantoni *et al.*, 2007) and, notably, ventilation is enhanced during exercise at high altitude at the same time as the arterial oxygen saturation is low, and both of these influences affect cerebral oxygenation (Imray *et al.*, 2005). A reduction in MCA *V*mean is also demonstrated during heating (Wilson *et al.*, 2006), and CBF decreases during exercise in the heat, equally associated with marked hyperventilation (Nybo *et al.*, 2002a), may provoke so-called central fatigue (Nybo and Nielsen, 2001b).

The second important influence on CBF, cerebral autoregulation, indicates that CBF stays more or less stable within a wide range of MAP, often indicated to be between 60 and 150 mmHg (Paulson, Strangaard and Edvinsson, 1990). Accordingly, the increase in MCA *V*mean during exercise is not explained by the increase in MAP. During post-exercise muscle ischemia, MCA *V*mean returns to the resting level (Jørgensen *et al.*, 1992b; Pott *et al.*, 2003), while MAP is maintained at the exercise level or it increases further if thigh cuffs are inflated before the end of exercise (Rowel, Hermansen and Blackmon, 1976). Also the finding that both the ^{133}Xenon clearance-determined CBF and MCA *V*mean remain stable during static exercise, associated with a similar increase in MAP as for dynamic exercise (Rogers *et al.*, 1990; Jørgensen *et al.*, 1992b), suggests that it is not the increase in MAP per se that

influences CBF. It takes, however, 2–3 s for cerebral autoregulation to be established and with marked changes in MAP in response to, for example weight lifting (MacDougall *et al.*, 1985) and rowing, there are parallel fluctuations in MCA *V*mean (Pott *et al.*, 1997). Also the marked increase in MAP at the onset of static exercise is associated with a transient increase in MCA *V*mean (Pott *et al.*, 2003), and such transient increases in MAP and MCA *V*mean are dominated by the Valsalva-like manoeuvre (Iwamoto *et al.*, 1987; Pott *et al.*, 2000) that is carried out in order to support the spine, especially during intense leg contractions.

Both the return of MCA *V*mean to the resting level during post-exercise muscle ischemia and the stability of CBF and MCA *V*mean during static exercise (Rogers *et al.*, 1990; Jørgensen *et al.*, 1992b) indicate that the increase in CBF during dynamic exercise is coupled to integration movement rather than reflecting an influence of pain and metabolic signals from the muscles referred to as the muscle pressor reflex (Mitchell, Kaufman and Iwamoto, 1983). The stability of CBF, but not necessarily of rCBF (Orgogozo and Larsen, 1979), during static exercise also indicates that the will to exercise, so-called central command, has little influence on CBF, although it does increase heart rate and MAP (Goodwin, McCloskey and Mitchell, 1972). Only with a PET evaluation of CBF during attempted contractions of paralyzed muscles is an increase in rCBF demonstrated corresponding to the insula (Nowak *et al.*, 1999, 2005), confirming the observations by SPEC during passive (Williamson *et al.*, 1997) and imagined exercise (Williamson *et al.*, 2002). Also some relay stations for a central influence on the circulation are identified by PET with an important role for the ventral and the dorsal periaqueductal grey area (VPG and DPG, respectively), but not for the globus pallidus interna (Green *et al.*, 2007). Of these areas of the brain, the DPG is of special interest because stimulation in this region elicits an increase in MAP (Green *et al.*, 2005). Yet, the influence of central command cannot elicit the full exercise response in MCA *V*mean or CBF. During attempted muscle contractions with a paralyzed arm, the normal increase in MCA *V*mean is lost (Jørgensen *et al.*, 1993a) as is the case for the SPEC-determined CBF (Friedman *et al.*, 1992). It remains, however, to be considered that no-load dynamic exercise is associated with only a small increase in CBF and MCA *V*mean (Jørgensen, Perko and Secher, 1992a). It appears, therefore, that integration of central command with the influence from integration of movement and the muscle pressor reflex are all needed to elicit the full exercise response in CBF and *V*mean in basal cerebral arteries likely to represent activation of enough areas of the brain to affect an integrated evaluation of flow.

Coupling between flow and brain metabolism remains elusive. Cytosolic NADH (nicotine adenine dinucleotide, reduced form) is a candidate sensor of cellular energy need and represents a possible coupling between blood flow and tissue metabolism (Ido *et al.*, 2001; Mintun *et al.*, 2004) in that NADH may provide a signal for vasodilation by the nitric oxide synthase system in the endothelial cells, I-NOS (Ido, Chang and Williamson, 2004). By physiological activation, the rate of glycolysis increases in all major tissues including muscle, heart, erythrocytes and brain. Lactate dehydrogenase (LDH) is abundantly expressed in all of these tissues and is believed to be in a near equilibrium state. Thus, the lactate-to-pyruvate (L/P) ratio of a given

cell reflects the cytosolic NADH-to-NAD^+ ratio multiplied by the LDH equilibrium constant, assuming one cytosolic compartment. Furthermore, changes in arterial plasma L and P, to the extent allowed by the respective monocarboxylate carriers, equilibrates with the cytosolic concentrations of the two metabolites and affects the redox state of the cells, which, in turn, may provide a signal for tissue perfusion. It has, therefore, been suggested that there is a coupling between the arterial L/P ratio and regional flow not only for the brain but also for skeletal muscles (Imray *et al.*, 2005). At least the results of one human study conform to that idea in regard to MCA *V*mean during rhythmic handgrip (Rasmussen *et al.*, 2006), but a more detailed evaluation is in need with determination of the time course for the two variables. Such an evaluation must be performed with a time resolution fast enough to differentiate if the L/P signal of the artery (and indeed intra-cellularly in the brain) is preceding the flow changes. According to the study by Lauritzen (2005), there is a ~5 s delay in the flow increase allowing for an arterial L/P signal as mediator of the increase, and intense exercise elicits significant arterial L/P increase after some 20 s (Rasmussen *et al.*, unpublished).

It should be mentioned also that exercise is associated with an increase in the blood haemoglobin level as fluid accumulates in the exercising muscles (Hanel *et al.*, 1997) with maybe, for humans, a small contribution from contraction of the spleen by sympathetic activation (Nielsen *et al.*, 1997). As for cardiac output (Krantz, Warberg and Secher, 2005), there is also for CBF a reverse relation to the level of haemoglobin in blood (Thomas *et al.*, 1977). The increase in CBF during exercise is, therefore, likely to be attenuated by the increase in haemoglobin or haematocrit, although no exercise data are available to evaluate that influence and eventual fluctuations in the blood haemoglobin level at the onset of exercise also need to be accounted for.

It is more controversial as to whether sympathetic activity influences CBF, which is relevant to exercise. Whole body exercise is especially associated with an enormous (~10 fold) increase in plasma catecholamines (Holmqvist *et al.*, 1986). The large increase in systolic blood pressure during intense exercise is a concern because it often exceeds the level considered to represent the upper limit of cerebral autoregulation. Yet, from a dynamic evaluation of cerebral autoregulation, the systolic increase in MCA velocity remains well controlled (Ogoh *et al.*, 2005a), while the diastolic velocity seems remarkably low both with marked fluctuations in blood pressure during rowing (Pott *et al.*, 1997) and in recovery from exercise (Ogoh *et al.*, 2007b). Also the finding that both MCA *V*mean and the NIRS-determined oxygenation of the brain are reduced from the supine to the upright position (Van Lieshout *et al.*, 2001) indicates an important role for sympathetic activation in regulation of CBF. In support, both MCA *V*mean and cerebral oxygenation increase when the standing position is supplemented by a leg crossing manoeuvre that attenuates sympathetic activity by enhanced cardiac output and the orthostatic influence on MCA *V*mean cannot be accounted for by the reduction in $PaCO_2$ (Immink *et al.*, 2006).

Of more direct relevance for exercise are the observations made during manipulation of cardiac output. During exercise, the increase in cardiac output is attenuated by the administration of a β-adrenergic antagonist, metroprolol, for example from 19 to 15 $l\,min^{-1}$ (Pawelczyk *et al.*, 1992) and the administration of the β-adrenergic

blocking agent also attenuates the increase in MCA *V*mean, typically to half of the increase normally seen during exercise (Ogoh *et al.*, 2005b). However, the normal 25% increase in MCA *V*mean manifests itself if, during exercise with metropolol, sympathetic activity to the brain is eliminated by blocking the stellate ganglion following the administration of a local anaesthetic (Ide *et al.*, 2000b). Similarly, in patients with cardiac insufficiency, there is a direct relationship between the increase in MCA *V*mean and the ability to increase cardiac output (Ide *et al.*, 1999b): and that the ability to increase cardiac output is important for the increase in MCA *V*mean is illustrated in the comparison of exercise with one leg only and two-legged exercise. During one-legged exercise, patients with cardiac insufficiency demonstrate the normal 25% increase in MCA *V*mean, but that is attenuated, or eliminated, during two-legged exercise (Hellström *et al.*, 1997). Thus, during exercise, MAP is the primarily regulated variable and flow to the brain and exercising muscles is not allowed to challenge the MAP regulated by the arterial baroreceptors integrating the influence from central command, the muscle pressor reflex and central blood volume (Secher and Volianitis, 2006).

Maybe the most striking and direct demonstration of the ability of the sympathetic nervous system to influence CBF is following administration of an α-agonist drug such as phenylephrine. In that situation, MCA *V*mean and cerebral oxygenation decrease markedly and that takes place in spite of an equally marked increase in MAP (Figure 10.2). Thus, α-sympathetic activity is able to overcome both the influence of $PaCO_2$ and cerebral autoregulation on CBF. Control of the elevated MAP during exercise, by the arterial baroreceptors modulating total peripheral resistance (Ogoh *et al.*, 2005b), appears to include regulation of CBF and, in the baboon, sympathetic control of CBF is well established (Meyer, Yoshida and Sakamoto, 1967). Also the blood glucose level enhances MCA *V*mean at rest, but the normal level is maintained during rhythmic hand grip, and administration of glucose does not affect dynamic cerebral autoregulation at rest nor during exercise (Kim *et al.*, 2007).

Whether perfusion of the human brain is influenced significantly by sympathetic activation may seem of academic interest rather than of clinical importance. Yet, during anaesthesia, where it is obviously not possible to get response from the patient, MAP is monitored and used for assurance of whether CBF is preserved according to what is considered the normal range for cerebral autoregulation (Paulson, Strangaard and Edvinsson, 1990). When MAP decreases to, for example 40 mmHg during induction of anaesthesia, there may be a need to administer phenylephrine. However, even at such a low MAP, cerebral oxygenation is usually preserved (Figure 10.3) and the administration of phenylephrine causes a decline in cerebral oxygenation. Preservation of cerebral oxygenation during hypotensive anaesthesia depends on an unchanged central blood volume in the CBF, and frontal lobe oxygenation declines at an MAP of ~80 mmHg when a reduction in the central blood volume is established by, for example head-up tilt (see Figure 10.3) (Madsen *et al.*, 1995; Jørgensen *et al.*, 1993b) or lower body negative pressure (Waldemar *et al.*,

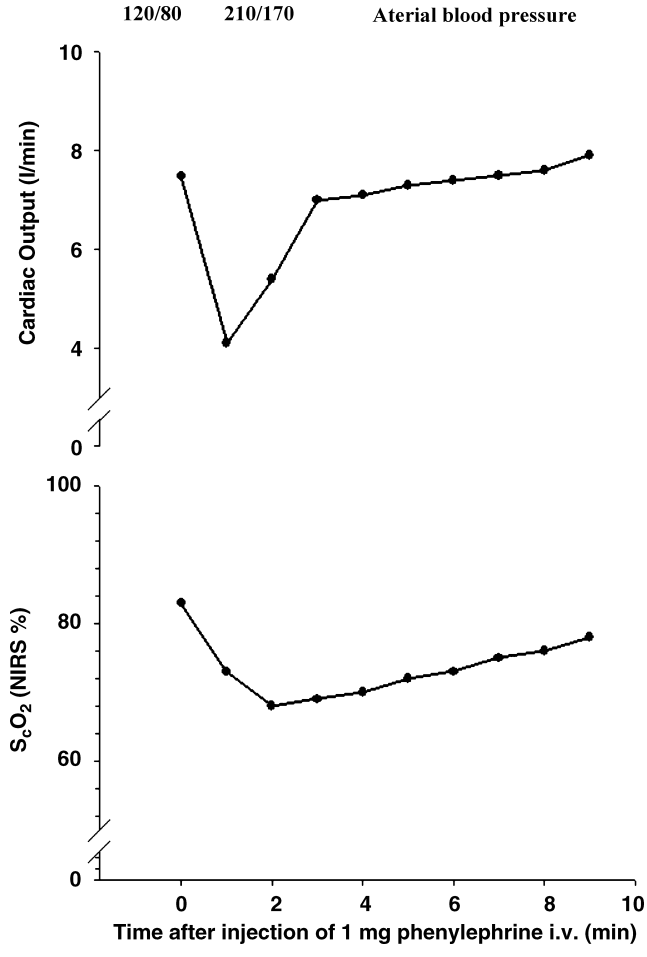

Figure 10.2 Effect of administration of 1 mg phenylephrine i.v. at supine rest on cardiac output and frontal lobe oxygenation for one subject. The increase in systolic and diastolic arterial pressures is shown. Although blood pressure exceeds the level normally considered the upper limit for cerebral autoregulation, frontal lobe oxygenation and the middle cerebral artery mean flow velocity (not shown) decrease.

1989). Accordingly, monitoring of blood pressure during anaesthesia is no guarantee that CBF is maintained. Either, the usual monitoring of heart rate and blood pressure needs to be supplemented by a continuous reading of the central blood volume, for example by thoracic electrical impedance (Matzen *et al.*, 1991), a reading of cardiac output or, ideally, by monitoring CBF or brain oxygenation noninvasively by NIRS (Madsen and Secher, 1999) in order to prevent the often reported deteriorated transient or permanent mental function following anaesthesia.

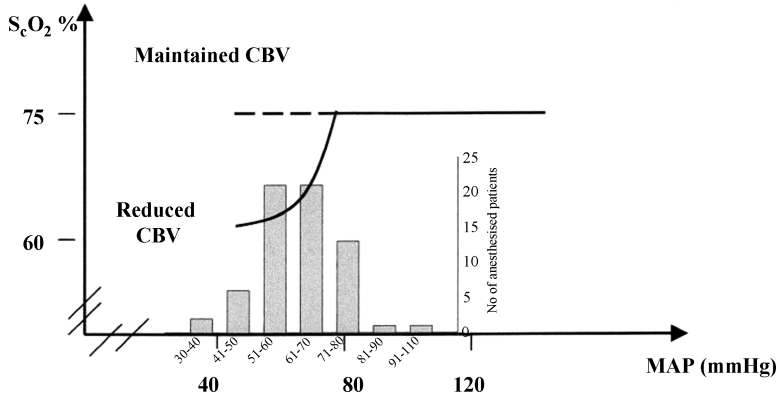

Figure 10.3 The near infrared spectroscopy-determined frontal lobe oxygenation following the introduction of anaesthesia (broken line) and during head-up tilt-induced hypovolemic shock. (Data from P. Nissen et al. 2009 and from Madsen *et al.*, 1998.)

10.2 Cerebral oxygenation

As mentioned, cerebral oxygenation increases when the brain is activated, including that induced by exercise (Ide and Secher, 2000). This increase in cerebral oxygenation during activation is in contrast to the other large excitable tissue, the skeletal muscles in which activation (work) is associated with reduced oxygenation. Also, skeletal muscles maintain their activity despite oxygen de-saturation exceeding 90% (Åstrand *et al.*, 1964), while the brain tolerates only little more than a 10% reduction in its average oxygenation (Madsen and Secher, 1999). As judged by the fMRI- or NIRS-determined oxygenation, brain activation seems to be associated with surplus perfusion and there may be good reasons for why that is necessary. The capillaries within skeletal muscle are positioned in direct contact with the muscles cells, but there is a barrier between the brain capillaries and the neurones. Brain capillaries are not different from capillaries in other vascular beds but, within the brain, the capillaries are protected by extension of the astrocytes covering the entire capillary network and that layer constitutes the blood–brain barrier. The average diffusion distance for oxygen in the brain is 30 μ, defining the magnitude of the average oxygen gradient from the capillary to the mitochondria. This oxygen gradient may be steep and in some cases limit oxygen consumption. A mathematical model illustrates that over a distance as short as 2–3 μ perpendicular to the capillary, the mitochondrion may either be fully or nonfunctional (Quistorff, Chance and Hunding, 1977). The same model also suggests that with data for oxygen consumption, inter-capillary distance and venous oxygen tensions, the mitochondria in the brain are well supplied with oxygen. This does not, however, rule out that under activation, a combination of high oxygen consumption and low capillary oxygen tension, the diffusion distance for oxygen may become critical in certain locations and, therefore, an increase in flow is in need. Thus, enhanced neuronal metabolism

requires an elevated oxygen gradient as there, also in contrast to skeletal muscles, is not considered to be any capillary recruitment within the brain.

It is possible to calculate changes in brain capillary oxygen tension and, accordingly, in the mitochondrial oxygen tension during activation, including that induced by exercise (Rasmussen *et al.*, 2007). From such calculations, maximal exercise is, despite the increase in capillary oxygenation, associated with a reduced mitochondrial oxygen tension as CBF becomes affected by the reduction in $PaCO_2$ besides an eventual reduction in the arterial oxygen content during whole-body exercise (Nielsen *et al.*, 1998, 1999). However, even during maximal, whole-body exercise, the cerebral mitochondrial oxygen tension does not reach such a low level as established during sub-maximal exercise at a 10% inspired oxygen fraction (Nybo and Rasmussen, 2007).

To what extent a reduction in the cerebral mitochondrial oxygen tension during maximal, whole-body exercise affects the function of the brain remains to be established. With electromagnetic stimulation of the brain following maximal ergometer rowing, there is little indication for affected cerebral function and, in fact, after exercise there is facilitation of the brain influence on the motoneurons (Carlsson, 2007). On the other hand, with the marked cerebral de-saturation developed during hypoxia, slow contractions are affected, while there is no influence on fast movement (Rasmussen *et al.*, 2007). If that observation is confirmed, it suggests that motoneurons controlling slow twitch muscle fibres are more susceptible to hypoxia than those controlling fast twitch muscle fibres. In other words, it is the ability to perform refined, or graded, movement that becomes affected the most by hypoxia and from both electrical (Nybo *et al.*, 2003) and by electromagnetic stimulation of the femoral nerve following exercise (Amann *et al.*, 2006), strenuous exercise is demonstrated to provoke some level of central fatigue. Interestingly, central fatigue does not affect the electro-mechanical activation of the muscle which, in fact, seems to be enhanced (Minshull *et al.*, 2007). Thus central fatigue is a manifestation of an inability to maintain rather than an inability to generate force (Rube and Secher, 1991), and that is what would be expected if the contribution of the slow twitch muscle fibers to the contraction becomes less important, as demonstrated during partial neuromuscular blockade (Secher, Rube and Secher, 1983).

10.3 Cerebral metabolism

With the uncertainty that remains as to the expression of changes in CBF and, thereby, $CMRO_2$ during exercise, it is comfortable that changes in cerebral metabolism can be expressed independently of those in CBF. As demonstrated by Fox and Raichle (1986) for visual stimulation, cerebral activation is associated with a reduction in the metabolic ratio defined as the ratio of the apparent oxygen and glucose uptake for the visual cortex. Normally, the brain takes up oxygen and glucose for carbohydrate in a ratio of 6:1 indicating that the brain oxidizes the carbohydrate completely at the rate it is taken up. The balance in cerebral aerobic metabolism is supported by two

fundamental observations. One is that a person becomes unconscious within seconds after the brain is deprived of its supply of oxygen, as exemplified during cardiac arrest. The other contention is that the possibility for the brain to develop significant anaerobic metabolism is limited by a low level of both PCr and glycogen compared with skeletal muscle. While the first notion is obvious, the role of anaerobic metabolism for the brain may have to be revised with regard to the glycogen content of the brain, which seems not to be trivial. Although the brain glycogen content is confined to the astrocytes, in humans it reaches 5–6 mM (glycocyl units) in grey and white matter and 13 mM within the hippocampus, with only marginally lower levels for the pig (Dalsgaard *et al.*, 2007). Thus, for the astrocytes taking up less than 20% of the brain volume, the glycogen level approaches that established in skeletal muscles. It is likely that anaerobic metabolism plays an important role in providing enhanced energy turnover to feed cerebral activation although it, as for skeletal muscles, cannot support maintained activity. Moreover, the brain may release a small amount of lactate at rest and especially during hypoxemia or in response to an extremely low MAP, if the low blood pressure reflects a limited cerebral perfusion.

The work of Fox and Raichle (1986) provided evidence that cerebral metabolism is more varying than indicated from the results obtained by a Kety–Schmidt-determined $CMRO_2$. In the PET-based evaluation by Fox and Raichle, the resting cerebral metabolic ratio was as low as 4.1 and during exposure to flashing light, it decreased further to 2.8 in the visual cortex. In a follow-up study, Madsen *et al.* (1999) found the cerebral metabolic ratio for the brain as a whole to decrease to 5.4 during exposure of subjects to a mental task. Such a deviation in the cerebral metabolic ratio for the whole brain seems, however, trivial compared to those developed during exercise (Dalsgaard, 2006).

After providing a subject with an arterial and internal jugular venous catheter, needed to determine the cerebral metabolic ratio from blood samples, the ratio is seldom 6. Rather a 'resting' value of 5.7 is demonstrated and, if blood samples are obtained immediately after catheterization, the cerebral metabolic ratio is even lower and recovers gradually towards 6 during a following resting period. It seems that the cerebral metabolic ratio decreases in response to the anxiety associated with catheterization and the expectations involved in participating in a physiological experiment, and that may have been a contributing cause for the very low initial cerebral metabolic ratio reported by Fox and Raichle (1986), when the subjects were confined in a PET scanner.

During sub-maximal exercise, the cerebral metabolic ratio remains relatively stable for as long as the workload is not demanding (Ide, Horn and Secher, 1999a; Nybo *et al.*, 2003). Only when the work rate becomes demanding, such as when it is increased to exhaustion, is the cerebral metabolic ratio reduced to reach a nadir of, for example 4.7 (Ide, Horn and Secher, 1999a). Whether the workload becomes demanding depends not only on its absolute level as by the administration of a neuromuscular blocking agent, strength can, by titration, be reduced to any chosen level and eventually neuromuscular blockade induces paralysis of all skeletal muscles, as practised for tracheal intubation in preparation for surgical anaesthesia.

For unknown reasons, the diaphragm is the muscle least affected by a neuromuscular blocking agent (Johansen, Jørgensen and Molbech, 1964; Jørgensen *et al.*, 1966; De Troyer, Bastenier and Delhez, 1980) making it possible to perform even intense exercise at a severely reduced strength level. An otherwise trivial sub-maximal workload thereby becomes demanding or eventually requires a maximal effort and, in that situation, there is a marked reduction the cerebral metabolic ratio (Dalsgaard *et al.*, 2002). Similarly, when exercise is made difficult and painful by hindering leg blood flow by a venous or an arterial cuff around the thighs, the cerebral metabolic ratio is reduced (Dalsgaard *et al.*, 2003). Both the apparent influence from the will to exercise and the pain associated with exercise influence brain metabolism, although their separate influences do not seem to be as large as observed during control exercise, supporting the belief that many cerebral areas need to be activated to appreciate the global response. Also the reduction in the cerebral metabolic ratio progresses as more muscles are involved in exercise to a record low level of 1.7 during maximal ergometer rowing (Figure 10.4). Maximal ergometer rowing often involves a 2000 m all-out effort and, in that situation, the reduction in the cerebral metabolic ratio manifests at the onset of exercise (Fabricius-Bjerre, 2007).

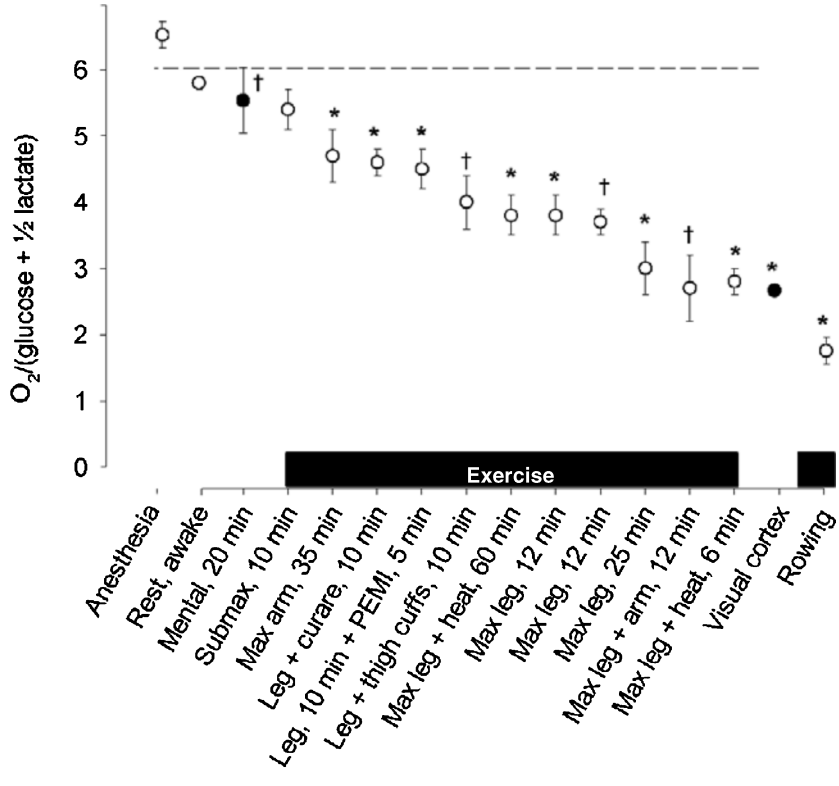

Figure 10.4 The nadir of the cerebral metabolic ratio during different types of activation paradigms. (Modified from Dalsgaard, 2006.)

At rest, the arterial lactate level of less than 1 mM is of little or no importance for the cerebral metabolic ratio. However, as blood lactate increases with work rate, lactate is taken up by the brain in proportion to its arterial concentration, which, for rowing, may exceed 30 mM (Nielsen, 1999). Thus, with the increasing lactate concentration during exercise, lactate is integrated in the cerebral metabolic ratio (oxygen uptake/uptake of glucose + $^1/_2$ uptake of lactate) (Ide *et al.*, 2000a) while the contribution of pyruvate is small (Rasmussen *et al.*, 2006). In support, the lactate taken up by the brain during exercise does not accumulate in the spinal fluid or within the brain tissue, at least not above the detection level of proton MR spectroscopy (about 2.5 mM) (Dalsgaard *et al.*, 2004a) and lactate is established as a substrate for the neurons (Pellerin, 2005). That is the case for lactate produced by glycolysis in astrocytes but, apparently, also for lactate taken up from blood (Quistorff et al. 2008). Integrating the lactate taken up by the brain during exercise means that there is an excess uptake of carbohydrate of 10–15 mmols of glucosyl units compared to what can be accounted for by the oxygen uptake, and that uptake of carbohydrate is of the same order of magnitude as the brain's glycogen level (Dalsgaard *et al.*, 2004a, 2007).

Little is known about why the reduction in the cerebral metabolic ratio takes place during activation of the brain. The uptake of carbohydrate in the brain during exercise is not associated with arterial-ventricular (a-v) differences for relevant hormones, including insulin, insulin-like growth factor and cortisol (Dalsgaard *et al.*, 2004c). However, the concentration of noradrenaline increases in the cerebrospinal fluid and the brain takes up ammonium, although it accumulates in the cerebrospinal fluid only during prolonged exercise and then related to the expressed perceived exertion (Nybo *et al.*, 2005). The only intervention that has been shown to affect the cerebral metabolic ratio is the administration of the nonselective β-adrenergic blocking agent propranonol in the rat (Schmalbruch *et al.*, 2002) and confirmed by preliminary human data (Figure 10.5). On the other hand, the cardioselective β-adrenergic blocking agent metroprolol does not affect the cerebral metabolic ratio during exercise in humans (Dalsgaard *et al.*, 2004b). Together with the observation that the cerebral metabolic ratio decreases in proportion to the involved muscle mass and the work rate and, thus, in proportion to the lactate level, may well indicate that the cerebral metabolic ratio decreases in response to the, equal to lactate, exponential increase in plasma adrenaline with work rate, although that needs to be established. One avenue to explore the influence of adrenaline on the cerebral metabolic ratio would be to evaluate the response to static exercise. Static exercise involving a more than 30% of maximal voluntary contraction hinders muscle blood flow (Bonde-Petersen, Mørk and Nielsen, 1975) and is, therefore, associated with a low lactate level in blood, while there is no restriction on the release of adrenaline from the adrenal gland.

Prolonged exercise also offers an opportunity to separate the adrenaline and blood lactate concentrations. During prolonged exercise, there is little or no increase in blood lactate, but the cerebral metabolic ratio decreases when exercise has lasted for so long that it becomes demanding. This may be due to a decrease in the muscle glycogen level, an intolerable heat stress, dehydration or, eventually, because of a decreasing blood glucose level (see Figure 10.6) (Nybo *et al.*, 2003). Taken together,

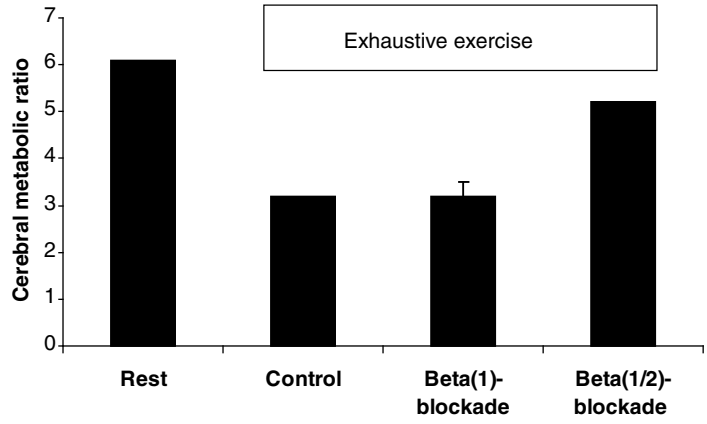

Figure 10.5 Changes in the cerebral metabolic ratio (uptake of oxygen/(uptake of glucose + $^1/_2$ lactate)) during exhaustive exercise in humans with or without administration of propranolol (nonselective beta 1 and 2 blockade). Data represent the mean for three subjects. (Data ($n = 7$) for administration of metropolol (selective beta 1 blockade; mean ± SE) from Dalsgaard *et al.* (2004b) and Larsen et al. 2008.)

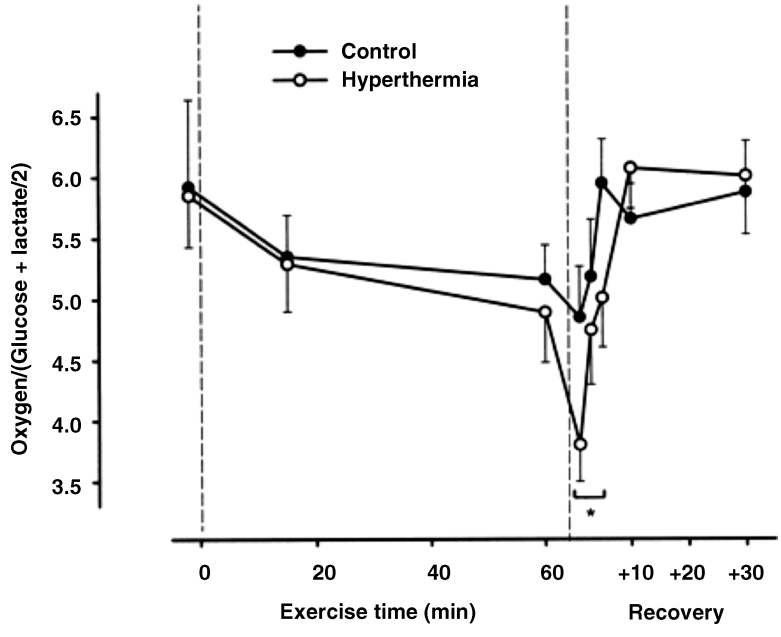

Figure 10.6 Cerebral metabolic ratio during and after exercise with a normal (control) or elevated (hyperthermia) core temperature. Values are means ± SE for eight subjects. * Different from rest and the corresponding value in control trial ($P < 0.05$). Blood lactate was <2 mM when the cerebral metabolic ratio decreased. (Adapted from Nybo *et al.* (2003).)

the available data lead to the hypothesis that the cerebral metabolic ratio decreases in response to exercise by adrenergic stimulation of cerebral metabolism and it becomes interesting to evaluate whether central stimulating drugs affect cerebral metabolism.

Another potent regulator of the brain glucose metabolism during exercise is the cytokine interleukin-6 (IL-6), which increases markedly in the circulation during exercise. The main contributor to the increase in IL-6 during exercise is working skeletal muscles (Febbraio and Pedersen, 2002). Glucose ingestion during exercise, however, attenuates the release of IL-6 from the muscles, as glucose uptake in the working muscles is enhanced (Febbraio *et al.*, 2003). Similarly, it could be that the release of IL-6 from the brain during exercise reflects an energy crisis within the brain and the release of IL-6 from the brain is larger during the second exercise bout when the exercise trial is repeated, and independent of the temperature that is reached (Nybo *et al.*, 2002b). It is not known, however, whether supplementation of carbohydrates affects the release of IL-6 from the brain during prolonged exercise, although IL-6 does not seem to respond to short lasting maximal exercise (Dalsgaard *et al.*, 2004a). In addition, intense exercise does not affect the brain handling of tumor necrosis factor or heat shock protein and their cerebrospinal fluid concentrations do not increase in response to exercise (Steensberg *et al.*, 2006). Also, there is no uptake or release from the brain of brain natriuretic peptide during exercise (Schou *et al.*, 2005).

Insight to brain metabolism during exercise may also be obtained by determination of brain-derived neurotrophic factor (BDNF). At least at rest, administration of glucose eliminates the release of BDNF from the brain (Krabbe *et al.*, 2007), while during prolonged exercise, administration of glucose attenuates the tryptophan concentration and its cerebral uptake and, maybe, also the synthesis of serotonin or 5-hydroxytryptamine (5-HT) in the brain (Blomstrand *et al.*, 2005). Together these results indicate that ingestion of glucose (and fluid) during prolonged exercise prevents a build up of 5-HT within the brain and it has been suggested that branched chain amino acids be provided in preparation for prolonged exercise, although it has not yet been possible to provide convincing evidence for its effect.

The brain may be in need of anaerobic metabolism for accelerated metabolism during activation in response to a mental effort during exercise. But the brain has also the capability to provide at least some enduring anaerobic metabolism. Even at rest there is typically a small release (0.04 mmol min^{-1}) of lactate from the brain and with a marked decrease in blood pressure during surgery, the release of lactate is larger. Furthermore, during exercise in hypoxia, there may be no uptake of lactate in the brain, although the blood lactate level is enhanced (Nybo and Rasmussen, 2007). The results suggest that lactate is taken up by the brain according to the blood lactate level but that the uptake is compensated for by an equal release of lactate from the brain. An evaluation by stable isotopes is needed for the evaluation of the intermediate glucose and lactate metabolism in the brain during hypoxia.

10.4 Acute hypoglycemia

The central role of glucose for brain metabolism is demonstrated by the acute decrease in blood glucose level associated with dysregulation of diabetes mellitus. It is well known that many diabetic patients experience some 'feeling' before the blood glucose level reaches a critical level of approximately 2.5 mM. Thus, they are able to digest some carbohydrate-rich food or, eventually, inject glucagon before brain metabolism becomes severely affected and the patient loses consciousness. Interestingly, it seems that tolerance to hypoglycemia is genetically determined. The tolerance to a low blood glucose level is superior in those diabetic patients with the II gene profile to the angiotensin converting enzyme (ACE) compared to those possessing the DD gene (Pedersen-Bjergaard *et al.*, 2001); that is glucose tolerance may be coupled to blood pressure regulation or the two phenomena are related in a yet undetermined way. It is of equal interest that mountaineers making it to the top of the mountain also show the II genetic profile to ACE (Patel *et al.*, 2003). At this stage, it can only be speculated that tolerance to a low blood glucose level is important for performance in situations where access to food is limited, although the II gene profile may also be linked to other factors associated with enhanced athletic performance. Thus, among the Australian rowers participating in the World Championships or the Olympic Games, there is an over-representation of athletes with the II ACE gene (Gayagay *et al.*, 1998).

In regard to central fatigue, it also seems likely that the amount of magnesium in the brain has an important role in stabilizing brain metabolism during exercise as magnesium enhances CBF (Ludbrook, James and Uptorn, 1999). At least in the rat, a magnesium sulphate injection increases the amount of brain glucose and pyruvate, at the same time as it attenuates the increase in lactate during forced swimming (Cheng *et al.*, 2007). In many situations an elevated pyruvate level enhances all metabolites when it is challenged, for example during reperfusion of ischemic organs (Mallet *et al.*, 2005). Depletion of magnesium from the brain during strenuous exercise would be an indication of impaired brain metabolism and, hence, reduced physical performance. At least it appears that it could be determined that plasma magnesium is not at a low level before planning to participate in maximal or demanding exercise.

10.5 Conclusions

Continuous provision of oxygen and glucose is essential for brain metabolism. However, at least during intense exercise, lactate uptake by the brain seems to substitute for the uptake of glucose (Kemppainen *et al.*, 2005) while, during prolonged exercise, blood lactate does not increase and it is critical that glucose, besides fluid, is provided throughout the endeavour. Provision of glucose during exercise is critical, especially during mountaineering, where body temperature depends on a continuous high metabolic rate and inactivity following a lowered

blood glucose level may be lethal. It is recommended that subjects carry a store of carbohydrate when prolonged exercise is planned in a cold environment, as is well established for diabetic patients in danger of a sudden decrease in the blood glucose level. This is so because weather conditions may change rapidly, therefore, prolonging the duration of the trip unpredictably and, especially at high altitude, cerebral metabolism is limited by oxygen availability and mountain sickness may occur.

10.6 Future research

From the era of the Kety–Schmidt method for evaluation of CBF, brain metabolism was found to remain stable during exercise. That is in sharp contrast to the dynamics of cerebral metabolism revealed by evaluation of inflow to the brain. Also, the consideration that the brain relies only on oxygenation of glucose has been changed dramatically by the fact that the brain may take up as much lactate as glucose during intense exercise and that, together, the carbohydrate uptake by the brain is much larger than can be accounted for by the uptake of oxygen. On the other hand, the mechanisms that control CBF and changes in metabolism during exercise need to be evaluated. It is likely that the use of stable isotopes will make it possible to evaluate the intermediate carbohydrate metabolism for the brain in humans. For that purpose, studies in the rat indicate that an evaluation of the importance of magnesium for cerebral metabolism in fatiguing exercise needs to be established, and electromagnetic stimulation of the brain could provide an avenue for elaboration of functional consequences linked to deviations in brain metabolism associated with reduced blood glucose level.

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PART 3

CHRONIC EXERCISE AND COGNITION

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11

An integrated approach to the effect of acute and chronic exercise on cognition: the linked role of individual and task constraints

Caterina Pesce

11.1 The gap between acute and chronic exercise research

In the panorama of the scientific literature concerning the relationship between physical activity and cognitive functioning, two main areas may be recognized: the effects of acute and chronic exercise on cognition. Sitting at the intersection of these two areas, this chapter focuses on the moderating role that chronic physical/sport training and other individual constraints may have on the effects of acute exercise on cognition.

The possible interplay between the effects of acute and chronic exercise on cognitive function has received limited consideration, with very little in the more recent literature. This is probably due to the fact that researchers have invested their primary effort to go beyond early, mainly atheoretical research methods that largely limited the importance of previous evidence, both for basic and applied sciences, in favour of newer research grounded on established theories of cognitive functioning. To this aim, researchers have progressively narrowed their attention to specific aspects of the exercise–cognition relationship that could be embedded in current theories of brain functioning, with the acute and the chronic exercise areas being examined independently.

On the one side, the impact of chronic exercise on cognition has primarily grown within the framework of cognitive aging theories that do not include the acute exercise view. The priority of this research area is to verify whether physical exercise

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significantly contributes to healthy aging (Colcombe and Kramer, 2003) or healthy development (Sibley and Etnier, 2003) and to determine the parameter values of the physical training that are associated with the largest positive effects on cognitive performance. Also, individual characteristics are considered, with the majority of the studies focusing on elderly or special populations such as older adults affected by secondary aging syndromes, or children and adolescents affected by developmental disorders or obesity (Davis et al., 2007; Kramer, Erickson and Colcombe, 2006). Only rarely have studies been conducted on young healthy adults (Hansen *et al.*, 2004).

In contrast, the impact of acute bouts of exercise has been primarily studied in the young adult population (Tomporowski, 2003a). Fewer studies have examined the effects of acute physical exercise on children's cognitive performance (Tomporowski, 2003b) and research on older populations is almost absent with the exception of two studies conducted with late middle-aged adults and older adults, respectively (Netz *et al.*, 2007; Pesce *et al.*, 2007a).

Although research concerning the impact of acute and chronic exercise on mental processing has mainly developed on separate tracks centred on different age groups, there is an important commonality: both of these research areas are moving toward more recent cognitive neuroscientific and psychophysiological perspectives that highlight the selective nature of the effects of physical exercise on cognitive function. The development of new theoretical underpinnings, in turn, is associated with methodological approaches that orient the choice of the variables to be investigated, that is to say those variables which are hypothesized to influence the exercise–cognition relation from the actual theoretical perspective.

With specific regard to acute exercise, researchers have devoted more attention to the role of task variables than to the role of individual differences deriving from the effects of chronic exercise. In fact, the earlier view on exercise as a stressor that induces increases in arousal and allocatable resources was mainly developed by manipulating physical task constraints such as exercise intensity and duration (McMorris and Graydon, 2000). More recently, a growing body of literature has dealt with the issue of whether different cognitive processes or information processing stages are affected differently by acute bouts of exercise. This theoretical interest is associated with a corresponding choice of the experimental variables of interest, with the essential factors being represented by such constraints of the cognitive task as complexity (computational variables) and nature (executive versus nonexecutive demands) (e.g. Coles and Tomporowski, 2008; Davranche and Audiffren, 2004; Dietrich and Sparling, 2004). The combined manipulation of cognitive and physical task constraints has contributed to the understanding that executive and complex tasks, as compared to nonexecutive and easier tasks, are differently affected by the intensity and duration of the physical exercise (Brisswalter, Collardeau and Arcelin, 2002; Tomporowski, 2003b), and that differences even exist between executive task sub-sets (e. g, Sibley, Etnier and Le Masurier, 2006). However, the amplitude and direction of the effects of exercise on executive functions seem also to depend on the time relation between physical and cognitive task. Consistent facilitation effects have been found in 'off-task' exercise research (e.g. Kamijo *et al.*, 2007; Tomporowski

et al., 2007a), whereas contradictory findings emerge from 'in-task' exercise research (e.g. Dietrich and Sparling, 2004; Pontifex and Hillman, 2007; Grego *et al.*, 2005; Pesce *et al.*, 2002).

Composing divergent results from older and more recent research is rendered difficult by the fact that until recently, research in this area was still lacking in standardization as regards the operationalization of physical and cognitive task conditions. Moreover, to override the difficulty of interpreting available results, it is necessary to consider that physical and cognitive task demands represent only a part of the constraints acting on the acute exercise–cognition relationship. In fact, this relationship can also be influenced by individual characteristics such as age and gender and, most interestingly, by individual constraints that derive from chronic exercise and sport training, such as physical fitness, sport-specific cognitive expertise and motor coordination ability (Figure 11.1).

11.2 Individual constraints on the acute exercise–cognition relationship: the role of chronic exercise effects

In their comprehensive meta-analytic review, Etnier *et al.* (1997) examined the effects of both acute and chronic exercise on cognitive functioning. The 134 studies that were considered relevant yielded 1260 effect sizes for subsequent analysis, but there were only six effect sizes from studies using mixed designs that combined acute and chronic exercise. For this reason, the influence of moderator variables within this sub-set of studies was not analysed. However, it should be noted that the overall effect size of these few studies (0.54) was larger than those of the sub-sets for studies with cross-sectional, chronic-longitudinal or acute designs. To my knowledge, no further mixed acute–chronic studies have been published in the subsequent years in scientific journals. The few available studies (Gutin, 1966; Weingarten, 1973; Zervas, Danis and Klissouras, 1991) suggest, on the whole, that an interaction between acute and chronic exercise effects exists. The interaction seems to consist of larger benefits of acute exercise on cognitive performance for highly fit individuals than for their less fit counterparts. Unfortunately, several methodological differences do not allow for thorough comparison and definitive conclusions. These few studies considered different age classes, involved fitness training programmes and acute bouts of exercise of different intensity and duration and employed different mental tasks that were not specifically targeted to tax the selective nature of the exercise–cognition relationship.

Gutin (1966) submitted a large sample of college students to an acute bout of combined physical and mental exertion followed by a battery of complex mental tasks. Then, the author committed half of the participants to 12 weeks of fitness training and repeated the acute physical and mental stress followed by the cognitive testing protocol. Although no differences in cognitive performance between the

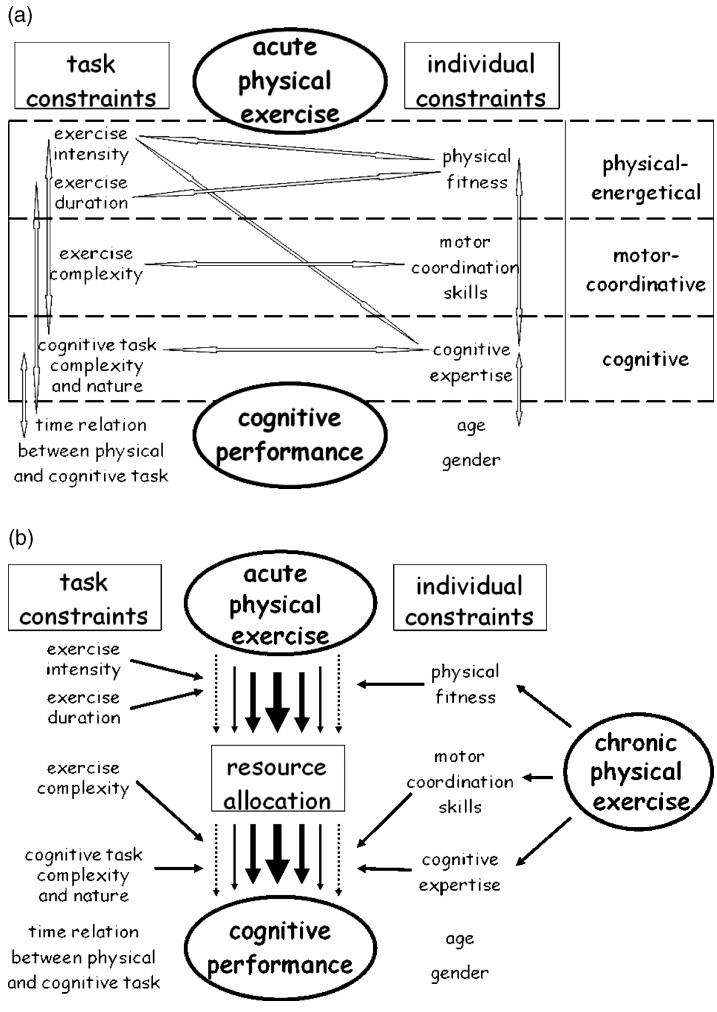

Figure 11.1 Schematic representation of the effects of individual and task constraints on the acute exercise–cognition relation, with particular reference to the individual constraints deriving from chronic exercise: (a) arrows represent the interactions, reported in the literature, between individual and task constraints (horizontal arrows) and within the sub-sets of individual and task constraints, respectively (vertical arrows); (b) arrows represent the relations hypothesized in the literature.

experimental and control groups emerged, the author found that individual increments in fitness level within both groups predicted the degree of mental performance improvement from pre- to post-test. This result can be interpreted as a fitness effect on cognitive efficiency, whereas an interpretation in terms of acute–chronic exercise interaction is weakened by the mixed, physical and mental, nature of the acute stressor administered before the cognitive test, and by the absence of a control condition in which cognitive testing was decoupled from acute exercise.

Weingarten (1973) applied a similar intervention procedure dividing the participants into two sub-samples and assigning one group to seven weeks fitness training. Then, he tested the mental performance of both groups during and immediately after an intense bout of exercise. His results support the hypothesis that enhanced aerobic fitness is associated with better cognitive performance immediately after an acute bout of exercise. Also, they shed some light on how the interaction between physical fitness and cognitive task constraints affects the short-term after effects of acute exercise on cognitive performance. With increasing task complexity, in fact, the physically trained group showed a cognitive advantage over the untrained group. As compared to the Gutin (1966) study, Weingarten (1973) employed a more complex design that involved cognitive testing both during and after physical exertion, but in this study a control condition is also missing.

Zervas, Danis and Klissouras (1991) examined the effects of acute physical exertion on performance on a visual discrimination task in pre-adolescent twins, who were randomly assigned to a six months training or nontraining period. At the end of this period, they performed the cognitive task twice, before and after an acute bout of 25 min treadmill running. A third group of age-matched controls performed the cognitive task twice, but resting between the two test sessions. Acute exercise led to better performances in the case of both trained and untrained groups and, more interestingly, the average improvement was largest for the trained group, suggesting the existence of interactive effects of acute and chronic exercise. The strength of this study was the comparison of pre- and post-exercise performances on the cognitive task, the presence of a control group that did not undergo the acute exertion and the assignment of twins to training or nontraining groups to minimize baseline differences between groups.

In summary, these older studies contain some relevant information regarding the influence that chronic exercise might have on the relationship between acute exercise and cognition. Nevertheless, given the extreme paucity and methodological dissimilarity of longitudinal studies that couple physical training interventions with the cognitive testing during or immediately after acute exercise, the present chapter takes into consideration cross-sectional evidence for the role of chronic exercise on the acute exercise–cognition relationship. The potential problem with cross-sectional studies, which must be taken into account, is that effects of the individual variables of interest (i.e. physical fitness, sport-specific cognitive expertise and motor coordination skill) may be confounded by cohort effects. For instance, fitness-related differences in cognition could be due, in part, to differences in socio-cultural variables that co-vary with the commitment to sport/physical activity and may influence mental performance.

Studies which combine cross-sectional measures of chronic exercise with acute bouts of exercise are more frequent than those employing a real acute–chronic mixed design, but are still a minority as compared to the large body of acute exercise research that focuses on the constraints of physical exercise and cognitive task without including the constraints deriving from training-related individual differences. This is surprising, given the claim of several authors that the direction and

magnitude of the effects of acute exercise on cognitive function may vary as a function of individual difference variables (e.g. Tomporowski, 2003b).

11.3 Effect of physical fitness: links to exercise intensity and to the time relation between physical exercise and cognitive task

Among the individual differences deriving from chronic participation in physical activity or sport, the one that has been most commonly considered in acute exercise research is physical fitness. In the chronic exercise research, there is robust evidence that aerobic fitness improvements produce beneficial effects on cognitive functioning particularly in aging (e.g. Colcombe and Kramer, 2003). In contrast, the existing findings relative to the effect of aerobic fitness level on cognitive performance during or immediately after an acute bout of exercise are contradictory.

On the one side, some authors demonstrated that physical fitness positively influences the acute exercise–cognition relationship both in young adults (Brisswalter *et al.*, 1997; Heckler and Croce, 1992; Sjöberg, 1980) and in children with mild mental retardation (Croce and Horvat, 1995). The individual fitness level also interacts with exercise task constraints since, for fit individuals, in contrast to unfit ones, the beneficial effects on cognition of acute exercise of moderate intensity seem to be maintained or even more pronounced under conditions of maximal intensity (Brisswalter *et al.*, 1997) and long duration (Heckler and Croce, 1992). However, other studies could not demonstrate any fitness effect on the acute exercise–cognition relationship (Magnièe *et al.*, 2000; Themanson and Hillman, 2006; Tomporowski, Ellis and Stephens, 1987; Travlos and Marisi, 1995; Tsorbatzoudis *et al.*, 1998). The time relation between physical exertion and cognitive task performance might account for the presence or absence of fitness effects. In fact, with only one exception (Sjöberg, 1980), all studies that have revealed a fitness effect belong to the 'in-task' exercise research aimed at verifying whether physical fitness modulates the effects that an acute bout of exercise produces on a concomitant cognitive performance. Brisswalter *et al.* (1997) suggested that physical fitness would reduce the physiological constraints and the attentional demands of the physical task, thus allowing fit individuals to optimize their performance in a concomitant cognitive task. This cognitive-energetic explanation may also account for the absence of fitness effects revealed by 'off-task' exercise research that studies the short-term after effects of acute bouts of exercise. In fact, the proposed optimization of resource sharing in the case of fit individuals would no longer be necessary after the end of the physical task.

Within the 'off-task' exercise research, a consistent absence of fitness effect is also reported across different task intensities and durations (Travlos and Marisi, 1995; Tsorbatzoudis *et al.*, 1998). The authors of an acute exercise study with brain electrophysiological measures of information processing (Magnièe *et al.*, 2000) wondered why they could not replicate the modulating effect of fitness level on

specific components of event-related brain potentials (ERPs) found by Polich and Lardon (1997) in a chronic exercise study. They argued that this contradiction might depend on the composition of the high-fitness group. Highly fit individuals in most studies are athletes, whose fitness levels may co-vary with the expertise in information processing and motor coordination that they develop to cope with their sport-specific demands. If the high-fitness group, as in the case of Polich and Lardon (1997), is mainly composed of athletes practising such open skill sports as ball games, their cognitive expertise, instead of fitness level itself, might be responsible for the individual differences found in the modulation of brain activity. In contrast, in the study by Magnièe *et al.* (2000), the aerobic fitness level did not co-vary with the cognitive expertise, since the high-fitness group was homogeneously composed of cyclists who do not share with ball game players high levels of cognitive effort. Nevertheless, cyclists' fitness levels probably co-vary with their skill in coordinating cycling movements. Since cycling is the physical exertion most commonly used for 'in-task' exercise research, the interpretation of differential acute exercise effects in cyclists and sedentary controls in terms of fitness effect would be weakened by the associated difference in skilled cycling performance. The higher the cycling skill, the less one would expect the dual task effect of pedalling and performing a concomitant cognitive task to be. Thus, when investigating the acute–chronic exercise interaction, the effects of chronic exercise cannot be merely conceived in terms of physical fitness levels, but must be also considered, more broadly, in terms of cognitive and coordinative skill levels.

11.4 Effect of cognitive expertise: links to cognitive task complexity, exercise intensity and duration, and age

To comprehend the role of individual differences in cognitive and motor coordination skills, one must take into account the key concept of resource allocation. There is a large consensus regarding the hypothesis that the effects of acute bouts of physical exercise on cognitive performance are mediated by variations in the amount of resources available for mental processing (Brisswalter, Collardeau and Arcelin, 2002; McMorris and Graydon, 2000; Tomporowski, 2003b). The allocatable resources theory is central in cognitive-energetical models applied to the acute exercise–cognition relationship (Kahneman, 1973; Sanders, 1983), as well as in cognitive psychophysiological perspectives that measure exercise-induced changes in the amount of allocated resources in terms of amplitude variation of specific ERP components (e.g. Kamijo *et al.*, 2007; Pontifex and Hillman, 2007; Yagi *et al.*, 1999).

However, there is a large heterogeneity of findings concerning whether acute exercise is responsible for more effective or ineffective resource allocation. Several authors reporting a facilitation effect of acute exercise on reaction speed suggested that more processing resources are rendered available during physical effort (e.g. Davranche and Audiffren, 2004; Pesce *et al.*, 2002, 2003). In contrast, other authors

claimed that the enhancement of reaction speed under physical effort is paralleled by diminished resource allocation, as reflected by event-related brain activity indices (Yagi *et al.*, 1999). A reduced resource allocation is specifically postulated to explain impaired performance on executive tasks during exercise, probably due to competitive demands in processing resources (Dietrich and Sparling, 2004; Pontifex and Hillman, 2007). Given these divergences, it can be hypothesized that the mediating effect of resource allocation is moderated by further variables that contribute to determine direction and magnitude of the exercise-induced changes in cognitive performance. These moderator variables can be identified as individual and task constraints. Earlier research (Paas and Adam, 1991) has shown that the direction and magnitude of the effects of acute exercise on the resources available for the cognitive task performance (facilitation versus dual task effect) may depend on the nature and complexity of the cognitive task. On the one hand, cognitive task complexity affects the acute exercise–cognition relationship while, on the other hand, perceived complexity varies with the individual level of cognitive expertise (Delignières, Brisswalter and Legros, 1994).

The moderating effect of cognitive expertise on the exercise-related availability of cognitive resources has still received relatively little attention. With the exception of an individual differences study by Sibley and Beilock (2007), where the effects of acute exercise on cognition were evaluated as a function of individual differences in cognitive baseline performance, researchers have focused on the cognitive expertise deriving from the practice of sports characterized by high demands on cognitive flexibility. The intriguing study conducted by Delignières, Brisswalter and Legros (1994) explicitly addressed this issue by contrasting the cognitive performance of 20 expert fencers with that of 20 athletes practising sports that did not require the same cognitive expertise, in order to control a possible bias related to physical fitness. Cognitively expert athletes showed better performance speed than their nonexpert counterparts, with progressive enhancements occurring as physical exertion increased, whereas an opposite, detrimental trend was observed in cognitively nonexpert athletes. These results suggest that cognitive expertise may have a high explanatory value for the acute exercise–cognition research, helping explain the lack of agreement that exists among studies. Above all, it may help to contrast the results reported in studies involving athletes with those involving nonathletes. In fact, unfortunately, many studies conducted with various athletes neither included a control group, nor contrasted experienced with novice athletes (Chmura *et al.*, 1998; Davranche and Audiffren, 2004; Davranche, Audiffren and Denjean, 2006a; Grego *et al.*, 2005; Legros *et al.*, 1992; McMorris *et al.*, 1999), whereas only a few studies have (Cereatti *et al.*, 2009; Delignières, Brisswalter and Legros, 1994; Marriot, Reilly and Miles, 1993; McMorris and Graydon, 1996a; Pesce *et al.*, 2007a, 2007b; Tenenbaum *et al.*, 1993). The majority of the studies mentioned were conducted with fast ball games players, and particularly with soccer players, are highly representative of skilled perceiving, decision-making and acting under temporal pressure, situational uncertainty and high levels of physical workload.

On the whole, these studies support the hypothesis that cognitive expertise allows individuals to better profit from the benefits of acute exercise on cognitive performance and that cognitive expertise also interacts with the physical task constraints (i.e. intensity and duration) and cognitive task constraints (i.e. complexity). Beneficial effects of exercise on cognitive performance of experienced athletes have been reported for visual attention, visual search, decision-making and choice reaction speed. Visual search, decision-making and choice reaction speed seem to be positively affected by exercise of moderate as well as maximal intensity, but only when athletes are well experienced, whereas performance of novices or nonathletes seems to be unaffected by acute exercise or even deteriorated in the case of exercise bouts of high intensity or long duration (Marriot, Reilly and Miles, 1993; McMorris and Graydon, 1997a).

With regard to visual attention, results (Pesce *et al.*, 2007a, 2007b; Cereatti *et al.*, 2009) revealed a more complex interplay between cognitive expertise, cognitive task complexity and age. In a series of experiments, the authors verified the effects of a sub-maximal bout of acute exercise on reaction time in two different types of visual attentional tasks. The first measured the time needed to enlarge and narrow the attentional focus at foveal and parafoveal locations, while the second measured the time needed to move a large and a narrow focus of attention in the peripheral visual field. Each experiment was composed of a sub-set of two tasks that differed in the amount of endogenous control over attention and inhibitory processes. Although the authors did not explicitly address the issue of acute exercise effects on executive function, the two tasks differed in the amount of executive control. This manipulation of task complexity is relevant because the more complex task showed a high validity to change, being sensitive to several individual constraints (cognitive expertise, age and gender).

In a study conducted with high-level soccer players and physically active controls (Pesce *et al.*, 2007b), a facilitation effect of acute exercise on reaction speed was found for nonathletes both in the easier and the more complex attentional tasks, whereas for players only in the more complex one. The authors suggested that although physical exercise induces an activation of allocatable resources, the amount of resources allocated to the attentional task varies as a function of individual expertise. Referring to the concept of cognitive effort (Kahneman, 1973; Sanders, 1983) as it was embedded in the acute exercise theory (Davranche and Audiffren, 2004; Tomporowski, 2003b), Pesce *et al.* (2007b) argued that the less complex attentional task was not sufficiently challenging for the highly experienced players, thus leading to relatively low levels of cognitive effort. This, in turn, would limit the exploitation of the resources available during exercise. Moreover, in the more complex task, the reaction speed of players during exercise was facilitated in a selective manner, with an improvement in only the most time consuming attentional operation, whereas in the case of controls the facilitation occurred regardless of attentional task conditions. This indicates that cognitive expertise enables players to perform a more selective and skilled allocation of the resources available during exercise, whereas inexperienced individuals adopt an undifferentiated, even distribution of resources throughout the task.

It must be pointed out that freeing allocatable resources, as postulated by theories of exercise-induced increases in arousal, represents only the first step in the mediated exercise–cognition relationship. Physical fitness is hypothesized to influence this step by acting as a moderator of the acute exercise–arousal relationship (Brisswalter *et al.*, 1997). However, 'freeing' does not necessarily mean 'exploiting'. *How* and *how efficiently* the freed resources are allocated to an ongoing cognitive task seems to depend on cognitive expertise related to task difficulty and cognitive effort.

In a sport developmental study, Cereatti and colleagues (2009) examined the moderating role of age by investigating the effects of acute bouts of exercise on visual attention orienting and focusing of skilled young orienteers. They argued that already at adolescent age, such skilled attenders as orienteers are better able than nonorienteers to allocate the resources available during physical exercise to a concomitant psychomotor task characterized by high demands on endogenous attentional control, as demonstrated by a more pronounced benefit of exercise on their attentional performance. To avoid a possible bias related to deliberate physical activity, the authors contrasted young orienteers with a sample of co-aged individuals who were as physically active as the orienteers. Thus, the novelty of this study is that it identifies the moderating effect of sport-related cognitive expertise on the exercise–attention relationship in youths. Until now, the effect of cognitive expertise on the acute exercise–cognition relationship has been investigated almost exclusively in young adults practising sports with high cognitive demands (see Tomporowski, 2003b), except for a unique study with older orienteers (Pesce *et al.*, 2007a).

Pesce *et al.* (2007a) showed that in the case of older adults, the facilitation effect of sub-maximal workloads on reaction speed that is reported for younger individuals (Pesce *et al.*, 2003) is reduced to a nonsignificant level, regardless of whether they are skilled orienteers or naïve to the sport. It seems that, whereas in younger adults, the arousal-induced increase in allocatable resources outweighs the dual task effect of performing the attentional task while cycling, this is not true in older adults. However, the authors wondered why, at rest, the attentional performance of older orienteers seems to be preserved from the age-related deterioration observed in older nonorienteers but it is strongly disrupted by a concomitant physical task, despite the fact that orienteers are skilled in coupling visual attentional performance with concomitant physical effort. They concluded that it might depend not on the energetical but on the coordinative demands of the physical task. Since with aging, dual task interference increases (Verhaeghen *et al.*, 2003) and motor coordination declines (Capranica *et al.*, 2004) the control of cycling movements may be very resource expensive for both older orienteers and nonathletes who are not skilled cyclists, thus competing for limited resources with the attentional psychomotor task. A theoretical interpretation of the data of older orienteers in terms of allocatable resources theory seems possible, but it remains an issue for further research as to whether a high skill level in motor coordination, as can be maintained by older adults with extensive training (Capranica *et al.*, 2005), will allow them to combine a cognitive and a physical workload without suffering from strong dual task effects. More generally, there is a need to comprehend the role of the coordinative complexity

of the physical task and the individual level of motor coordination skill within the acute exercise–cognition relationship.

11.5 Effect of motor coordination skills: links to physical exercise complexity, intensity and duration

The most common explanation for decrements in cognitive performance during acute exercise is the dual task hypothesis, which is based on the assumption of resource sharing between tasks. In this light, the complexity of the physical task represents a key factor according to which individuals may operate a trade in the amount of resources allocated in performing the physical and the cognitive tasks (Brisswalter, Collardeau and Arcelin, 2002). Unfortunately, the majority of acute exercise studies are based on cognitive tasks in which performance is indirectly measured in terms of reaction accuracy (errors) and reaction time (i.e. length of the period from the presentation of a target stimulus to the initiation of the overt response to this stimulus). Usually, reactions are not manipulated in terms of coordination complexity but consist in simple finger depressions that necessitate very simple pre-programming.

Only a few studies have utilized movement time (i.e. period from movement initiation until its completion) as a dependent variable. This imbalance between reaction time and movement time studies limits the comprehension of the potential role played by physical task complexity. As revealed by movement time analysis (McMorris *et al.*, 2005b), facilitation effects of acute exercise occur when the limbs used for the motor component of the cognitive task are not the ones that are being exercised, with a maximum of facilitation during maximal and even supra-maximal exercise. In a further study, McMorris *et al.* (2005a) found that when the cognitive task performance requires, in contrast, complex whole-body movements involving the effectors that were just exercised, a maximal exercise bout has detrimental effects on movement time.

Earlier acute exercise research has devoted attention to the motor coordination demands of the physical task as related to its energetical demands (Brisswalter, Collardeau and Arcelin, 2002). The authors reported a previous study (Brisswalter *et al.*, 1995) demonstrating that reaction time performance was shortest at the energetically optimal pedalling rate (60 rpm) and at a freely chosen rate, which only slightly diverged from the energetically best one. A factor that is strictly related to the movement execution frequency is the level of attentional monitoring requested to coordinate the movements of the physical exercise. Brisswalter *et al.* (1997) tested the effects of different 'in-task' exercise intensities and found a detrimental effect on cognitive performance when the intensity was low (20% maximal aerobic power). They interpreted it as a physical-cognitive dual task effect that could not be overridden by the activating effect of physical effort because the intensity was too low for an exercise-induced increase in arousal to occur. In a successive study,

Davranche and Audiffren (2004) could not replicate this negative effect for the same exercise intensity of 20% maximal aerobic power. They argued that the absence of a dual task effect could be explained by the fact that in contrast to the previous study, individuals were not forced to maintain a required, externally paced pedalling rate. The freely chosen pedalling rate probably required lower demands on attentional monitoring of the cycling movements, thus eliminating the dual task effect. Moreover, Davranche and Audiffren (2004) utilized a sample of experienced ball games players whose cognitive expertise and motor coordination skills may have allowed them to perform the physical task with a very low attentional monitoring load. Thus, the interplay between motor coordination constraints and attentional control demands should be further investigated with reference to the individual level of cognitive and motor coordination skills.

Some interesting insights for future research derive from studies that have investigated physical–cognitive dual tasks to analyze the constraints imposed by the coordination mechanisms underlying the physical task performance (e.g. Zanone *et al.*, 2001; Monno *et al.*, 2002). These studies addressed the issue of the attentional cost of maintaining a bimanual coordination pattern at a given level of stability. In a dual-task paradigm associating a bimanual coordination task and a reaction time task, the authors utilized the reaction time task as a probe that measures the attentional costs associated with varying bimanual coordination patterns. The findings support the usefulness of a unified approach to the study of cognitive–coordinative dual tasks that encompass both the cognitive psychological human information processing view and dynamical systems models. Most interestingly, this approach is developing toward the manipulation of the energetical constraints of the physical task in addition to the purely coordinative ones. In fact, in two recent studies, typical manipulations of in-phase/anti-phase coordination mode and execution frequency are paralleled by the manipulation of the muscular load applied to the forearm muscles before the bimanual coordination test (Murian *et al.*, 2008a), the trial duration and resistance to motion during the coordination trial (Murian, Deschamps and Temprado, 2008b).

It is important to note that within this theoretical framework, equal importance is attributed to both individual and task constraints, in contrast to the unbalanced focus on task constraints that characterizes the existing approaches to the study of the effects of acute exercise on cognition. However, to my knowledge, the coordination-attention approach has still not been applied from an individual differences perspective that controls how the interplay between motor coordination and attentional load varies as a function of the motor coordination skill level acquired through chronic physical training. The same lack exists within the acute exercise research. Although some authors claim that the decreased efficiency in executive control functions during physical exertion may reflect the need to allocate resources toward the whole-body movements inherent to exercise (Pontifex and Hillman, 2007), no study has yet investigated the interplay between the coordination demands of the physical task and the individual level of motor coordination skills.

A further line of research could be represented by studies that analyze whether the enhanced efficiency of attentional and cognitive processes during or after acute

exercise may, in turn, be beneficial to actual motor performance of skilled performers. As an example, an intriguing study by Vickers and Williams (2007) with elite biathlon athletes showed that the effects of physical effort on shooting performance were moderated by changes in visual attention. Depending on exercise intensity, athletes performed a strategic control of attention that enabled them either to exploit the positive effects of acute exercise on their motor performance or to compensate for the detrimental effects associated with higher exercise intensities.

11.6 Bridging the gap between acute and chronic exercise studies

The research area concerning the effects of acute exercise on cognitive function has an enormous potential in several applied fields. However, an optimal exploitation of the scientific findings in this area for applied purposes is possible only under consideration of the separate and joint effects of both task and individual constraints on the exercise–cognition relationship. In other words, an individual differences approach is essential for an integrated approach to the effects of acute and chronic exercise on cognition. The individual differences perspective may strengthen the ergonomic implications that the effects of acute bouts of physical exercise on cognition have for occupational, military and sport settings, where important cognitive operations must be performed rapidly during moderate to heavy physical exertion. Within the individual constraints, a key role is played by the individual differences in physical fitness, cognitive expertise and motor coordination skills that derive from chronic physical training and sport practice (Figure 11.1).

Given the particular influence of cognitive expertise on the acute exercise–cognition relationship, it might be fruitful to also analyze its role from the cognitive psychophysiological perspective. Until now, acute exercise studies involving the measurement of event-related brain activity have not included cross-sectional measures of cognitive expertise (Grego *et al.*, 2004; Higashiura *et al.*, 2006; Hillman, Snook and Jerome, 2003; Kamijo *et al.*, 2004b, 2007; Magnièe *et al.*, 2000; Pontifex and Hillman, 2007; Yagi *et al.*, 1999). This is surprising since ERP components have shown a high measure of sensitivity relative to the sport-specific cognitive expertise, as determined by comparing skilled athletes with nonathletes (Di Russo *et al.*, 2006; Hung *et al.*, 2004; Pesce and Bösel, 2001; Zani and Rossi, 1991) or athletes of different expertise levels (Del Percio *et al.*, 2007) or athletes practising the same sport but with different competitive specialties (Rossi and Zani, 1991). The cognitive expertise of athletes practising sports characterized by high situation uncertainty is prevalently reflected by the modulation of neuroelectric indices of skilled attentional control (Pesce and Bösel, 2001) and executive inhibitory function (Di Russo *et al.*, 2006). It can be assumed that the ERP methodology applied to acute exercise research with athletes differing in terms of cognitive expertise and motor coordination skills might contribute to the interpretation of the contradictory results concerning whether

'in-task' exercise has facilitating or detrimental dual-task effects on executive control performance (Dietrich and Sparling, 2004; Pontifex and Hillman, 2007; Grego *et al.*, 2005; Pesce *et al.*, 2002).

Cross-sectional research should be paralleled by longitudinal studies that evaluate the effects of acute exercise on cognition before and after physical training programmes. We have yet to determine the role that long-term, physical training interventions, involving different levels of energetic, coordinative and cognitive demands, have on the effects of acute bouts of exercise on cognitive performance. Also interactions with further relevant individual characteristics such as gender (Pesce, Casella and Capranica, 2004) and age (Cereatti *et al.*, 2009; Pesce *et al.*, 2007a), related to the constraints of physical exercise and cognitive task should be considered. An integrated acute–chronic exercise approach should be systematically applied in life-span and developmental research. Elucidating the positive impact of periods of acute physical activity on cognitive performance of students practising different types and amounts of physical activity/sport may provide support for the implementation of structured physical activity in educational environments targeted to both physical and cognitive improvement. Finally, understanding the joint effects of aerobic fitness, cognitive expertise and movement coordination skills on the ability of older individuals to perform physical–cognitive dual tasks may offer important insights to trainers who want to optimize the functional abilities of aging people, thus significantly contributing to the maintenance of quality of life in everyday activities. The literature clearly indicates that complex inter-limb coordination is largely preserved from age-related deterioration in older trained individuals (Capranica *et al.*, 2005) and that cognitive-executive functions of older adults are positively affected by aerobic fitness training (Colcombe and Kramer, 2003) and can be substantially improved in older adults by means of specific dual-task training programmes (Bherer *et al.*, 2006). Therefore, it is to be expected that coupling coordinative and aerobic training with dual-task exercising would allow older adults to maintain the efficiency of resource allocation on cognitive-physical dual task performance. This may represent one important target of future mixed, acute-chronic exercise research.

12

Chronic exercise and cognition in older adults

Jennifer Etnier

The relationship between aging and cognition is well established, with research consistently showing that advancing age is predictive of worse performance on certain cognitive tasks (Salthouse, 2003; Schaie, 1994), greater declines in cognitive performance over time (Bors and Forin, 1995; Brayne *et al.*, 1999; Schonknecht *et al.*, 2005) and greater risk of Alzheimer's disease (Jorm and Jolley, 1998; Lindsay *et al.*, 2002; Rubin *et al.*, 1998). However, evidence from longitudinal studies indicates that age-related cognitive declines do not occur equally in all individuals (Albert *et al.*, 1995) and that some older adults experience 'successful aging' whereby they continue to have good health and perform well cognitively (Rowe and Kahn, 1997). Thus, cognitive decline is not an inescapable concomitant of aging and the identification of lifestyle factors that contribute to the maintenance of cognitive function is possible.

One lifestyle factor that has received empirical attention is regular participation in physical activity. The seminal study was conducted by Spirduso in 1975. In this study, a cross-sectional design was used to examine differences in reaction time as a function of age and regular involvement in racket sports. In support of an effect of age on cognition, results indicated that reaction time was faster for the younger adults (20–30 years) as compared to the older adults (50–70 years). Importantly, however, this effect was moderated by physical activity such that older adults, who were regularly involved in racket sports, performed more quickly than older adults who were inactive and, in fact, performed as quickly as the younger adults. Despite the particular limitation of using racket sports participants, who might logically have elected to participate in this particular form of physical activity because of innately fast reaction times, and the additional limitations inherent in all cross-sectional studies, this study was the impetus behind an area of research that has been growing rapidly and that has become increasingly complex. In particular, the research in this

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area has advanced from relatively simple, cross-sectional studies to more well-designed, complex studies including those using prospective designs to examine differences in cognitive decline over time; those using experimental designs to test causal relationships; and those using animal models, neuroimaging techniques and other methods to test potential mechanisms of the relationship.

12.1 Theoretical underpinnings

There are a host of theories that have been proposed to explain the positive relationship between chronic physical activity and cognition, and these can be categorized into those which focus upon the specificity of the cognitive effects; those which focus on the mechanisms that are likely to underlie the effect; and those which focus on the effects of aging on cognition and consider physical activity to be one of many possible moderators of this effect.

Specificity of the effect

Hypotheses which focus on the specificity of the cognitive effects have recently been described by Colcombe and Kramer (2003) and include the speed hypothesis (Dustman *et al.*, 1984; Spirduso and Clifford, 1978), the visuospatial hypothesis (Shay and Roth, 1992; Stones and Kozma, 1989), the effort hypothesis (Chodzko-Zajko, 1991; Chodzko-Zajko and Moore, 1994) and the executive function model (Hall *et al.*, 2001; Kramer *et al.*, 1999). All of these hypotheses are based on the supposition that those tasks that are the most cognitively demanding for older adults (i.e. speeded tasks, visuospatial tasks, tasks that are effortful, executive function tasks) should benefit the most from participation in physical activity. The hypothesis which is currently receiving the most empirical attention by far is the executive function model which posits that physical activity will have its greatest benefits on cognitive activities that require executive control. Executive control tasks are defined as consisting of four components: volition, planning, purposive action and effective performance (Lezak, Howieson and Loring, 2004). Evidence suggests that advancing age has a greater impact on executive control tasks than on nonexecutive control tasks (Mayr and Kliegl, 1993), thus these types of tasks are expected to be most sensitive to the potentially beneficial effects of physical activity. In support of the executive function hypothesis, meta-analytic evidence (Colcombe and Kramer, 2003) has shown that the effects of physical activity on cognitive function are largest for tasks that are categorized as executive function tasks.

Mechanisms of the Effect

Hypotheses which focus on the mechanisms of the effect include the cardiovascular fitness hypothesis (North *et al.*, 1990); the cerebral circulation hypothesis

(Dustman *et al.*, 1984; Spirduso, 1980); the neurotrophic stimulation hypothesis (Dishman *et al.*, 2006); and the neural efficiency hypothesis (Dustman *et al.*, 1990). Historically, the cardiovascular fitness hypothesis has received the most empirical attention, however recent research with animals and studies using neuroimaging techniques with humans have focused on testing mechanisms that are implicated by the other three hypotheses. Most of these mechanisms have not been directly tested as mechanisms of the relationship. That is, the evidence relevant to these hypotheses consists of studies demonstrating that physical activity impacts the mechanism and separate studies demonstrating that these mechanisms are themselves predictive of cognitive function. To date, there only a few studies (van Praag *et al.*, 1999; van Praag *et al.*, 2005) in which any of these mechanisms have been directly tested in a single study as a mediator of the relationship between physical activity and cognitive function.

Physical activity as moderator of the aging effect

Studies focusing on the effects of aging on cognition include the cognitive reserve hypothesis and the frontal aging hypothesis. These hypotheses propose explanations for the effects of aging on cognition and have been considered viable explanations for the potentially beneficial effects of physical activity on cognition.

The cognitive reserve hypothesis posits that individuals who have greater cognitive reserve maintain their cognitive function better in the face of advancing age and are at less risk of dementia (Fratiglioni *et al.*, 2004; Scarmeas and Stern, 2003; Stern, 2002; Whalley *et al.*, 2004). This cognitive reserve may manifest as brain resources per se or as an ability to use existing brain resources more efficiently or flexibly (Stern, 2003). The underlying brain resources that are thought to contribute to a person's cognitive reserve include brain and cerebrospinal volume, brain metabolic activity, microvascular cerebral pathology and extent of damage due to oxidative stress (Stern *et al.*, 2005; Whalley *et al.*, 2004). Cognitive reserve is thought to be enhanced by a variety of lifestyle factors including formal education, occupational complexity and physical activity (Whalley *et al.*, 2004). It may be challenged by a variety of events including exposure to psychological stress, cerebral insult and the cumulative effects of advancing age. The hypothesis posits that individuals who have greater cognitive reserve, as a result of participation in physical activity, will maintain their cognitive abilities better in the face of challenges than will those with lesser cognitive reserve.

The frontal aging hypothesis suggests that advancing age impacts the cerebral structure and function of the frontal lobes (Dempster, 1992), which then influences the ability to perform frontally dependent cognitive tasks. This hypothesis is compatible with the executive function hypothesis because executive functions are thought to be frontally dependent (Hall *et al.*, 2001). However, in contrast to the executive function hypothesis, the frontal aging hypothesis focuses on the cerebral changes that accompany aging rather than the behavioural changes.

12.2 Empirical evidence

Since Spirduso's seminal study (Spirduso, 1975), numerous empirical studies have been conducted to examine the relationship between chronic physical activity and/or aerobic fitness and cognitive performance. When reviewed meta-analytically, cross-sectional studies demonstrate a moderate effect of physical activity participation or greater aerobic fitness on cognitive performance (Etnier *et al.*, 1999). However, studies using cross-sectional designs are hampered by the 'chicken-and-egg' problem. That is, it is not possible to discern from these designs whether the physical activity participation 'caused' better cognitive performance or whether better cognitive performance resulted in the participant having the necessary resources to be able to maintain higher levels of physical activity. This concern is particularly relevant given the fact that executive functions are expected to be particularly sensitive to physical activity participation and that involvement in voluntary lifestyle activities like physical activity is likely to be largely reliant upon executive functions, which allow one to plan and follow through on activities.

Prospective studies

Prospective studies represent an improvement over cross-sectional studies because baseline measures are taken to insure equality on cognitive performance measures at the initiation of the study. Thus, more confidence can be placed on conclusions that changes in cognition over time are due to differences in significant predictor variables (such as physical activity). Recently, a number of large-scale prospective studies have been conducted to examine the relationship between current (or past) levels of physical activity and the subsequent experience of cognitive declines. In all of these studies (except one), physical activity has been assessed using self-report survey measures of physical activity. The one exception is a study by Barnes *et al.* (2003) in which aerobic fitness was used as the predictor variable. The prospective studies can be categorized based upon whether the outcome variables were clinical cognitive outcomes (see Table 12.1) or standardized measures of cognitive performance (see Table 12.2).

In studies in which clinical cognitive outcomes were used, results from eight studies (Abbott *et al.*, 2004; Karp *et al.*, 2006; Larson *et al.*, 2006; Laurin *et al.*, 2001; Lindsay *et al.*, 2002; Podewils *et al.*, 2005; Rovio *et al.*, 2005; Yoshitake *et al.*, 1995) support a protective effect of physical activity against the experience of clinical cognitive decline, whereas results from four studies fail to support this conclusion (Broe *et al.*, 1998; Verghese *et al.*, 2003; Wilson *et al.*, 2002; Yamada *et al.*, 2003). Of the eight studies supporting the protective effects of physical activity, two also provide support for a dose–response relationship such that higher levels of physical activity result in greater protection against dementia (Abbott *et al.*, 2004; Laurin *et al.*, 2001). In studies in which standardized measures of cognitive performance were used as the outcome, results from six (Albert *et al.*, 1995; Barnes *et al.*, 2003;

Table 12.1 Prospective studies examining performance on clinical outcomes.

Study, *N*, gender, age at baseline, study length	PA measure and psychometrics?	Cognition	Controls	Findings
Abbott *et al.* (2004) Honolulu-Asia Aging Study 2257 M 71–93 ($M = 76.94$) 7 yrs	Physical Activity Index; # of miles walked/day → 4 categories: <0.25 mile/day, 0.25–1 mile/day, >1–2 miles/day, >2 miles/day No	Incident dementia based on Cognitive Abilities Screening Instrument, history, neuropsychological exam, lab work, and computed tomography.	Age, ApoE e-4, baseline cognitive score, decline in PA since mid adulthood, physical performance, education, BMI, yrs in Japan, profession, hypertension, diabetes, coronary heart disease, total cholesterol, HDL *Excluded participants due to prevalent stroke, Parkinson's, currently employed, physically not able to perform slight or moderate activity, smoking, use of a walker or cane	Hazard of dementia from least active group to most active group [reference]; *=significantly greater risk than most active group *Total dementia*: 1.93*, 1.75*, 1.33, 1.00 *AD*: 2.21*, 1.86, 1.88, 1.00 *Vascular dementia*: 1.17, 1.21, 0.16, 1.00 *Mixed and other dementia*: 2.83, 2.84, 2.00, 1.00
Broe *et al.* (1998) Sydney Older Persons Study 327 M and F (50% F) >75 ($M = 80.6$) 3 yrs	How often work in garden or yard, do active sports or exercises, go for walks → times per month No	Dementia and Alzheimer's disease	Age, sex, education	Not significant

(*continued*)

Table 12.1 (*Continued*)

Study, *N*, gender, age at baseline, study length	PA measure and psychometrics?	Cognition	Controls	Findings
Karp *et al.* (2006) Kungsholmen Project (Sweden) >75 yrs 732 M and F (74% F) 6 yrs	Interview: regular engagement in physical activity? Type and frequency → 4 categories based on # of moderately/highly intense activities (0, 1, 2–3, >3); 2 categories (0, >0) No	Incident dementia	Age, sex, education, cognitive functioning, co-morbidity, depression, physical function	Relative risk of dementia from least active [reference] to most active group; *=significantly more risk than most active group *4 categories* 1.0, 0.58*, 0.64, 0.59 *2 categories* 1.0, 0.68*
Larson *et al.* (2006) Adult Changes in Thought, ACT 1343 M and F (61% F) ≥65 ($M = 73.8$) 6.2 yrs (94% white)	Number of days/wk did each of the following for >15 min (walking, hiking, bicycling, aerobics or calisthenics, swimming, water aerobics, weight training or stretching, other exercise) → 2 categories: >=3×/wk or <3×/wk No	Incident dementia	Age, sex, alcohol, smoking, supplement use, education, ApoE, diabetes, hypertension, cerebro-vascular disease, coronary heart disease, self-rated health, physical performance, depression, cognitive functioning	Hazard ratios for inactive [reference] and active Dementia any type: 1.00, 0.68* AD only: 1.00, 0.69

Laurin *et al.* (2001) Canadian Study of Health and Aging, CSHA 4615 M and F (67.5% F) ≥65, 5 yrs	Frequency of PA (≥3×/wk, weekly, or less than weekly) and intensity (more vigorous, equal to, or less vigorous than walking) → 3 categories: high (≥3×/wk intensity > walking), moderate (≥3×/wk intensity = walking), low (all else) Yes	Cognitive impairment – no dementia (CIND); AD and other forms of dementia; Vascular dementia (VD)	Age, sex, education, family history of dementia, smoking, alcohol, NSAIDS, ADLs, IADLs, self-rated health, number of reported chronic diseases	Odds ratios from least active [reference] to most active. Trend significant: $^{*}=p<0.05$ $^{**}=p<0.001$. CIND **: 1.00, 0.66, 0.67, 0.58 AD*: 1.00, 0.67, 0.67, 0.50 VD: 1.00, 0.54, 0.70, 0.63 Dementia any type*: 1.00, 0.64, 0.69, 0.63
Lindsay *et al.* (2002) CSHA 4615 M and F (67.5% F) ≥65, 5 yrs	Engage in regular exercise → 2 categories: yes, no No	Risk of AD Note: more recent criteria for assessing AD (DSM, fourth Edition) than was used in Laurin *et al.*, 2001 (DSM, third Edition)	Age, sex, education	Odds ratios for inactive [reference] and active AD: 1.00, 0.69* OR not modified by ApoE status
Podewils *et al.* (2005) Cardiovascular Health Study 3375 M and F (59% F) >65 ($M=74.8$), 5.4 yrs	Modified Minnesota Leisure Time Activity Questionnaire = frequency and duration of PA (15 activities) in last 2 wks → METs → kcal/wk → quartiles; number of different activities in previous 2 wk → 4 categories (0–1, 2, 3, ≥4)	Clinical cognitive impairment	Age, sex, race, ApoE, education, difficulty in ADLs and IADLs, social network, social support, baseline cognitive score, white-matter grade	Odds ratios from fewest kcal/week or activities [reference] to most. Trend significant: $^{*}=p<0.05$ $^{**}=p<0.001$. Kcal/wk Dementia: 1.00, 1.22, 0.94, 0.85 AD: 1.00, 1.07, 0.92, 0.70

(continued)

Table 12.1 (*Continued*)

Study, *N*, gender, age at baseline, study length	PA measure and psychometrics?	Cognition	Controls	Findings
	No			Vascular dementia: 1.00, 1.32, 0.99, 1.03 # of activities Dementia **: 1.00, 0.90, 0.90, 0.58 AD*: 1.00, 0.73, 0.85, 0.55 Vascular dementia: 1.00, 1.09, 1.01, 0.65
Rovio *et al.* (2005) 1251 M and F 65–79, 21 yrs	Frequency of leisure time PA ('20–30 min and causes breathlessness and sweating') → 6 categories: daily, 2–3×/wk, 1×/wk, 2–3×/month, a few times/year, none No	Dementia; AD	Model 1: Age at re-examination, sex, education, follow-up time, and locomotor disorders; Model 2: Model 1 + ApoE ε4 genotype, midlife body-mass index, systolic blood pressure, cholesterol and history of myocardial infarction, stroke and diabetes mellitus; Model 3: Model 2 + smoking status, alcohol drinking	Odds ratios for active vs. sedentary [reference] Dementia Crude model: 0.55; Model 1*: 0.45; Model 2*: 0.46; Model 3*: 0.47 AD Crude model: 0.45; Model 1*: 0.34; Model 2*: 0.34; Model 3*: 035

Verghese *et al.* (2003) 488 75–85 ~5.1 yrs	Frequency of PA from list of 11 activities → activity days/wk summed for each of 11activities → 3 categories: <9 pts, 9–16 pts, >16 pts No	Incident dementia	Model 1: Age at enrollment, sex, educational level, presence or absence of chronic medical illnesses. Model 2: Model 1 + baseline scores on the Blessed test.	Not significant Hazard ratio based on PA score Model 1: <9 pts: 1.00; 9–16 pts: 1.06; >16 pts: 0.92 Model 2: <9 pts: 1.00; 9–16 pts: 1.44; >16 pts: 1.27
Wilson (2002) Chicago Health and Aging Project 835 M and F (59% F) >65 ($M = 76.0$), 4.1 yrs (55% white)	Recall of participation in activities over last 2 wk (from 1985 Health Interview Survey) → total weekly hours No	Incident AD	Age, sex, race, ApoE status, race x ApoE, time from baseline to follow-up, education, cognitive activity score	Not significant
Yamada *et al.* (2003) Adult Health Study 1774 M and F (73.2% F) >60 22–29 yrs	Physical activity index calculated from occupational and leisure activities No	Dementia (AD or vascular)	Age, sex, education	Not significant
Yoshitake *et al.* (1995) Hisayama, Japan 826 M and F >65 ($M = 73.6$) 7 yrs	PA at leisure and work → 4 categories No	Vascular dementia and Alzheimer's disease	Age, sex, baseline neuropsychological performance	RR = 0.20 for regularly moderate physical activity ($p < 0.01$)

Note: PA = physical activity, psychometrics? = is validity and reliability information provided for the measure of physical activity, controls = variables that were considered for inclusion as covariates in the analyses, M = men, F = women, M = Mean, HDL = high-density lipoprotein, AD = Alzheimer's disease, NSAIDS = non-steroidal anti-inflammatories, ADLs = activities of daily living, IADLs = instrumental activities of daily living, DSM = Diagnostic and Statistical Manual, METs = Metabolic equivalents, ApoE = Apolipoprotein E

Table 12.2 Prospective studies examining performance on standardized cognitive tasks. *Note*: PA = physical activity, psychometrics? = is validity and reliability information provided for the measure of physical activity, controls = variables that were considered for inclusion as covariates in the analyses, M = men, F = women, *M* = Mean, avg = average.

Study, *N*, gender, age at baseline, study length	PA and psychometrics?	Cognition	Controls	Findings
Albert *et al.* (1995) MacArthur Studies of Successful Aging 1119 M and F (55% F) 70–79 (*M* = 74.3) 5 yrs (81% white)	Current participation in strenuous activity (in daily activities around the house) No	Test battery (Boston Naming Test [BNT], spatial recognition from Delayed Recognition Span Test, Delayed incidental recall of BNT items, Similarities from Wechsler, figure copying)	Gender, age, education, race, income, alcohol use, smoking, chronic conditions, body mass, waist-to-hip ratio, physical function, DHEA-S, HDL, cortisol, mental health, life satisfaction, emotional support, social ties, efficacy, foot tapping speed, pulmonary peak expiratory flow rate, baseline score	Higher levels associated with less cognitive decline
Barnes *et al.* (2003) Sonoma California 349 M and F (49% F) >59 (*M* = 69) 6 yrs (97% white)	Graded maximal exercise test (peak VO_2) Yes	Modified MMSE, Trail Making Test Part B, Stroop Interference, Digit Symbol (DS), California Verbal Learning Test, Verbal fluency	Gender	Tertiles of Fitness (Trend significant for all at $p < 0.01$. Means from lowest fitness group to highest fitness group) *MMSE*: 28.5, 28.9, 29.2 Trails B: 12.4, 14.7, 17.0 Stroop: 39.8, 44.1, 48.2 DS: 23.9, 27.5, 30.2 Imm. recall: 6.6, 7.8, 8.2 Delayed recall: 7.3, 8.5, 8.8 Letter 's': 11.9, 12.6, 13.6 Animals: 16.5, 17.2, 18.3

Broe *et al.* (1998) Sydney Older Persons Study 327 M and F >75, (*M* = 80.6) 3 yrs	How often work in garden or yard, do active sports or exercises, go for walks → times per month No	Logical Memory I and II, Visual Reproduction I and II, Verbal fluency, National Adult Reading Test, Cube Copying, Clock Drawing, MMSE	Age, sex, education	Not significant
Dik *et al.* (2003) LASA 985 M and F (51% F) 62–85 (*M* = 74.9), 6 yrs	PA or sport participation that made you sweat or exhausted when 15–25 yr old (~50 yrs previously) → 4 categories: inactive (never or sometimes), low (<1–2 hr/week), moderate (3–9 hr/week), high (>10 hr/week).	MMSE, Alphabet Coding Task-15	Age, gender, verbal intelligence, socioeconomic status, early life physical work demands, current physical activity, smoking, alcohol use, diabetes mellitus, cardiac disease, depression	*Overall* *MSSE*: Not significant *Alphabet*: Not significant *Men only* *MSSE*: Not significant *Alphabet*: inactive = high < low = moderate *Women only* *MSSE*: Not significant *Alphabet*: Not significant
Lytle *et al.* (2004) MoVIES 929 M and F (64% F) >65 (*M* = 72.2) 2 yrs	Type, frequency and duration of exercise → 3 categories: high (≥30 min ≥3 days/wk), low (all other exercise), none; 2 categories: high (≥30 min ≥5 days/wk), low (all other exercise) No	MMSE	Age, sex, education, self-rating of health, baseline score	Reduced risk of cognitive decline for high exercisers (OR = 0.39) when defined as 3 d per week. Reduced risk of cognitive decline for high (OR = 0.45) and low (OR = 0.63) exercisers when defined as 5 d per week

(*continued*)

Table 12.2 (*Continued*)

Study, *N*, gender, age at baseline, study length	PA and psychometrics?	Cognition	Controls	Findings
Sturman *et al.* (2005) Chicago Health and Aging Project 4055 M and F (61%F) >65 yrs ($M = 73.5$) 6.4 yrs (39% white)	Recall of participation in activities over last 2 wk (from 1985 Health Interview Survey) → total weekly hours No	East Boston Tests of Immediate Memory and Delayed Recall, MMSE, Symbol Digit Modalities → averaged z-scores for each test	Age, sex, race, education, cognitive activities, vascular diseases, diabetes	Not significant
Van Gelder *et al.* (2004) FINE 295 M 64–84 ($M = 74.91$) 10 yrs	Frequency, duration and pace of walking and cycling during past week, avg time weekly on hobbies and gardening (summer/winter), avg time monthly on odd jobs and sports → 4 categories: ≤30 min, 31–60 min, 61–120 min, > 120 min/day Yes	MMSE	Age, education, smoking, alcohol use, country, mental activities, intensity	Duration: change over 10 yr positively predicted change in cognition over 10 yr ($p < 0.02$) Intensity: change over 10 yr positively predicted change in cognition over 10 yr ($p < 0.01$)

Weuve *et al.* (2004) Nurses Health Study 16 466 F 70–81 ($M = 74.2$) 8–15 yrs	Time per week in running, jogging, walking/hiking, racket sports, lap swimming, bicycling, aerobic dance or exercise machines, other vigorous activities, low intensity exercise. Usual pace: easy (>30min/mile), normal (21–30), brisk (16–20), very brisk (≤15) → METS → quintiles of PA, quartiles of walking. Number of flights climbed daily. Yes	Telephone Interview for Cognitive Status; East Boston Memory Test; category fluency; Digit Span Backwards	Age, education, husband's education, alcohol use, smoking, aspirin use, ibuprofen use, vitamin E use, balance problems, health limitations in the ability to walk a block, osteoarthritis, emphysema or chronic bronchitis, fatigue, mental health, antidepressant use, moderate to severe bodily pain, baseline score	Quintiles of Physical Activity (Trend significant: $^{*} = p < 0.05$ $^{**} = p < 0.001$. Odds ratios listed from lowest PA group [reference] to highest PA group) *TICS* **: 0, 0.17, 0.17, 0.28, 0.34 *CF**: 0, 0.04, 0.07, 0.18, 0.19 *WM***:0,0.12,0.13,0.20,0.25 *VM* **: 0, 0.04, 0.01, 0.04, 0.07 *Global* **: 0, 0.03, 0.01, 0.04, 0.06
Yaffe *et al.* (2001) Study of Osteoporotic Fractures 5925 F ≥65 ($M = 70.75$), 7.5 yrs	# of city blocks (or equivalent) walked each day → quartiles; city blocks walked combined with # of flights of stairs climbed each day → kcal/wk → quartiles No	Modified MMSE	Age, education, smoking, health status, functional limitation, depression, stroke, diabetes, hypertension, myocardial infarction, oestrogen use	Quartiles of Physical Activity (Trend significant for all at $p < 0.01$. Odds ratios listed from lowest PA group [reference] to highest PA group) Blocks: 1.00, 0.87, 0.63, 0.66 Kcal/wk: 1.00, 0.90, 0.78, 0.74

Note: LASA = Longitudinal Aging Study Amsterdam, MoVIES = Monongahela Valley Independent Elders Survey, FINE = Finland, Italy and the Netherlands Elderly Study; MMSE = Mini-Mental State Examination.

Lytle *et al.*, 2004; van Gelder *et al.*, 2004; Weuve *et al.*, 2004; Yaffe *et al.*, 2001) support a positive relationship between baseline levels of physical activity and subsequent cognitive performance, whereas the results from three studies did not support this relationship (Broe *et al.*, 1998; Dik *et al.*, 2003; Sturman *et al.*, 2005).

The primary limitation of most of the prospective studies is the use of self-report measures of physical activity. Although self-report measures of physical activity tend to have reasonable reliability (>0.60), validity correlations with objective measures of physical activity and with measures of fitness are variable and are lowest with the self-administered measures (Sallis and Saelens, 2000) that have typically been used in prospective studies. Further, because of their self-report nature, it is likely that these measures of physical activity may also reflect other types of activities that these individuals participate in such as social activities (e.g. dinner clubs, birding) and cognitive activities (e.g. crossword puzzles, card games) that might themselves contribute to the protection of cognitive abilities. Lastly, in most of these studies, physical activity measures were used that do not have established psychometrics (Albert *et al.*, 1995; Broe *et al.*, 1998; Dik *et al.*, 2003; Karp *et al.*, 2006; Larson *et al.*, 2006; Lindsay *et al.*, 2002; Lytle *et al.*, 2004; Podewils *et al.*, 2005; Rovio *et al.*, 2005; Verghese *et al.*, 2003; Yaffe *et al.*, 2001; Yamada *et al.*, 2003; Yoshitake *et al.*, 1995). Clearly, the reliance on self-reported measures of physical activity that do not have established psychometrics is a major limitation of these studies and may contribute to the variability in the results that have been found. Given that aerobic fitness can be measured objectively, the one prospective study (Barnes *et al.*, 2003) in which baseline aerobic fitness was used to predict cognitive performance six years later is of note. The results of this study indicated that higher levels of baseline aerobic fitness were predictive of better performance on the Modified Mini-Mental State Exam and on several measures of executive function.

In summary, results from 21 prospective studies have been mixed, with 14 studies supporting a positive relationship and 7 studies failing to support a relationship between baseline levels of physical activity and subsequent cognitive performance. Although there are an infinite number of possible explanations for these varied findings, it is important to point out that the sample sizes for the studies that failed to support a relationship (mean $N = 1256$) were typically smaller than those used in the studies that supported the relationship (mean $N = 3037$) suggesting that statistical power is one likely contributor. Future research using large samples and more objective measures of physical activity will be necessary to strengthen our confidence in concluding that physical activity is protective against subsequent age-related cognitive declines.

Experimental studies

Experimental studies have also been conducted in which physical activity is manipulated (typically with a goal of increasing aerobic fitness) to test the causal link

between chronic exercise and cognitive performance. The findings of these studies have also been mixed; thus, when examined using box-count methods, the results appear to be equivocal and the relationship with aerobic fitness is equally unclear. Meta-analyses, however, support a causal relationship between physical activity and cognitive performance. Colcombe and Kramer (2003) used meta-analytic techniques to examine the effects of 18 randomized controlled trials examining the effects of physical activity interventions on cognition in older adults. Their results showed that exercise is causally linked to cognitive performance with an average effect size (ES) of 0.48. Heyn, Abreu and Ottenbacher (2004) meta-analyzed the results of randomized controlled trials examining the effects of physical activity interventions on cognition in older adults with mild cognitive impairment and found an overall ES of 0.57. Thus, the experimental literature supports a moderate effect of physical activity on cognitive performance in older adults.

Clearly, one reason for the lack of consistency of the experimental studies is again related to statistical power. An average ES of approximately $^1/_2$ of a standard deviation (as observed in the meta-analytic reviews) necessitates a sample size of approximately 100 subjects to ensure statistically significant results (calculated using GPower v. 3.0.3 with two groups, power = 0.80, $\alpha = 0.05$). A second reason for the lack of consistency of the experimental studies is highlighted by some of the findings with respect to moderators of the relationship. Colcombe and Kramer (2003) found that the type of cognitive task moderated the effect such that significantly larger ESs, were obtained when cognitive measures assessed executive function (ES = 0.68) as compared to controlled (ES = 0.46), spatial (ES = 0.43), or speeded (ES = 0.27) tasks. Thus, the particular type of cognitive task used as the dependent variable can profoundly impact the likelihood of observing significant differences as a function of physical activity. Additionally, findings for moderators related to the dose of the physical activity (session duration, intervention length, aerobic fitness gain) indicate that the dose–response relationship between physical activity and cognitive performance is not yet clear. That is, the effect sizes for session duration (15–30 mins: ES = 0.18; 31–45 mins: ES = 0.61; 46–60 mins: ES 0.47), intervention length (1–3 months: ES = 0.52; 4–6 months: ES = 0.27; >6 months: ES = 0.67) and gain in aerobic fitness were not linearly related to cognitive performance.

Studies examining mechanisms

Relatively recent research has begun to test potential mechanisms of the relationship between chronic exercise and cognitive performance. Because of the invasive nature of the techniques necessary to test many of these mechanisms, the majority of these studies have been conducted using animal models. However, advances in neuroimaging techniques have allowed for very recent studies to test for mechanisms in human studies. The mechanisms that have been tested include aerobic fitness, cerebral structure, cerebral function, cerebral perfusion and neurotrophic factors.

Aerobic fitness

The hypothesis which has received by far the most empirical attention is the cardiovascular fitness hypothesis. This hypothesis was originally formalized by researchers studying relationships between physical activity and depression (North *et al.*, 1990). The hypothesis suggests that chronic physical activity benefits cognitive performance because of its effects on cardiovascular fitness. Many studies have either explicitly or implicitly been designed to test this hypothesis. That is, in cross-sectional studies, aerobic fitness has been used to differentiate the active and less active groups and, in intervention studies, physical activity programmes have been specifically designed to improve aerobic fitness and differences in aerobic fitness have been demonstrated as a manipulation check. However, despite the focus of numerous studies on aerobic fitness as a mechanism, the literature currently does not support this hypothesis. This conclusion is supported by findings of a recent meta-regression (Etnier *et al.*, 2006). In this meta-regression, ESs were calculated for the difference in fitness and for the difference in cognitive performance between a nonactive group and an active group, between an exercise group at the pre-test and at the post-test or between a control group and an exercise group at the post-test. Results of this study showed that regardless of the design of the study, effect sizes for the difference in aerobic fitness were generally not positively predictive of the effect sizes for the differences in cognitive performance.

Cerebral structure

Numerous studies have demonstrated that cerebral structure is affected by advancing age. Magnetic resonance imaging (MRI) techniques have shown that total brain volume (Courchesne *et al.*, 2000; Jernigan *et al.*, 2001; Tisserand *et al.*, 2000) and particular brain structures (including the hippocampus, prefrontal cortex, temporal and parietal cortices, cingulate cortex) are sensitive to aging effects in healthy older adults (Alexander *et al.*, 2003; Good et al., 2001; Jernigan *et al.*, 2001; Raz *et al.*, 2005; Resnick *et al.*, 2003; Rusinek *et al.*, 2003; Tisserand *et al.*, 2000). There is evidence that this decrease in volume is primarily a result of neuronal atrophy rather than a decrease in the number of neurons. Although the findings have been less consistent, longitudinal research has also shown that age-related losses of white matter are greatest in frontal and parietal regions (Resnick *et al.*, 2000; Resnick *et al.*, 2003); and a recent cross-sectional study using voxel-based morphometry (VBM) found that age-related declines in white matter were evident in frontal regions (Brickman *et al.*, 2006a) and partially mediated the relationship between aging and performance of executive function and memory tasks (Brickman *et al.*, 2006b).

Studies using animal models have consistently demonstrated that rats housed in 'complex environments', which provide opportunities for aerobic forms of physical activity, undergo changes in the cerebral cortex that differ from those of rats housed in sterile environments with limited opportunity for physical activity (Churchill *et al.*, 2002). For example, Black *et al.* (1990) and Isaacs *et al.* (1992) found that rats

that exercised aerobically for 30 days experienced significantly greater changes in cerebral vasculature than did nonexercising rats; and van Praag and colleagues (van Praag *et al.*, 1999a; van Praag *et al.*, 1999b) showed that aerobically exercised rats experienced neurogenesis in the hippocampus and performed better on cognitively demanding tasks than did sedentary rats. Thus, when the level of aerobic activity is manipulated in rodents, the findings suggest a causal relationship between aerobic activity and both cognitive performance and cerebral structure.

Research on the preservative effects of aerobic fitness on cerebral structure has been conducted with human subjects. Colcombe *et al.* (2003) used MRI to examine cerebral structure in older adults in relation to their aerobic fitness levels. They found declines in grey matter as a function of age in the frontal, parietal and temporal cortices, and decreases in white matter tissue in the anterior and posterior white matter tracts. Although the main effect for aerobic fitness was not significant, the interaction effect of aerobic fitness with age was significant. Aerobic fitness predicted less grey and white matter tissue loss in the same regions affected by advancing age. The authors concluded that aerobic fitness predicts patterns of cerebral structure that are consistent with aerobic fitness benefiting certain types of cognitive function in the face of age-related declines. Similarly, in older women, Erickson *et al.* (2006) found main effects for aerobic fitness on tissue volume in the frontal and prefrontal cortex. They also reported main effects for aerobic fitness on white matter tracts in the prefrontal region. Thus, these two studies with human subjects also support aerobic fitness as a predictor of cerebral structure and the findings are consistent with the observed behavioural findings (i.e. aerobic fitness is associated with changes in cerebral structure in areas of the brain that are important for the types of cognitive performance that have been shown to be associated with aerobic fitness).

Cerebral function

Age-related changes in cerebral function have also been documented, with differences particularly apparent in the prefrontal cortex (Tisserand and Jolles, 2003). In the prefrontal cortex, younger adults show hemispheric asymmetry in activation during task performance, while older adults show reduced hemispheric asymmetry, which has been interpreted as indicating compensatory mechanisms (Cabeza *et al.*, 2002; Reuter-Lorenz *et al.*, 2000). Rajah and D'Esposito (2005) conducted a meta-analytic review of the literature ($N = 22$ studies) and concluded that age-related differences in prefrontal function are region-specific with deficits in function in the right dorsal and anterior prefrontal cortices and dedifferentiation (reduced signal-to-noise ratios) in the bilateral ventral prefrontal cortex.

Two studies by Colcombe and colleagues (Colcombe et al., 2004) have examined the relationship between aerobic fitness and cerebral activation in older adults. Functional MRI (fMRI) measures were taken from older adults during performance of a selective attention task (Ericksen flanker test). In Study 1, fMRI and aerobic fitness measures were taken once. In Study 2, these measures were taken prior to and following six months of either an aerobic exercise programme or a nonaerobic

control condition. Results from Study 1 showed that higher levels of aerobic fitness were associated with better cognitive performance, with greater activity in the middle frontal gyrus (MFG), superior frontal gyrus (SFG) and superior parietal lobule (SPL), and with less activity in the anterior cingulate cortex (ACC). Results from Study 2 showed that the cognitive performance of the aerobically trained participants improved significantly from pre-test to post-test but did not improve for the control group. Additionally, at the post-test, the aerobic group showed significantly greater activity in the MFG, SFG and SPL, and significantly lower activity in the ACC than the control group during task performance. Thus, Colcombe and colleagues' cross-sectional data demonstrated a relationship between aerobic fitness and patterns of cerebral activation. Their experimental data suggest a causal relationship between aerobic fitness and better cognitive performance and between aerobic fitness and predicted patterns of cerebral activation in the frontal and parietal areas.

Cerebral perfusion

Aging has been shown to be associated with decreases in regional cerebral blood flow (CBF) in areas including the hippocampus, fronto-temporal and tempero-cingulate cortices (Larsson *et al.*, 2001; Pagani *et al.*, 2002; Takahashi *et al.*, 2005). Further, Alzheimer's disease is characterized by reduced CBF in several regions of the brain including the parietal cortex, temporal cortex and temporo-parietal cortex (Crawford, 1996; Kasama *et al.*, 2005; Matsuda, 2001; Stern *et al.*, 1992).

Very few studies have looked at the relationship between chronic physical activity and cerebral perfusion. Though animal studies have found that chronic physical activity results in increased CBF (Endres *et al.*, 2003; Swain *et al.*, 2003), only one published study has examined the relationship between chronic physical activity and CBF in humans. Rogers *et al.* (1990), who examined the relationship in recently retired older adults, found that retirees who were sedentary experienced declines in CBF and in cognitive performance over four years, while retirees who were physically active maintained their cognitive performance and CBF levels.

Brain-derived neurotrophic factor

Brain-derived neurotrophic factor (BDNF) is the neurotrophic factor which has received the most attention as a potential mechanism of the relationship between physical activity and cognition. BDNF plays a critical role in neural function and neuroprotection, promotes synaptogenesis and neurogenesis, and is important for learning and memory (Cotman and Engesser-Cesar, 2002; Vaynman and Gomez-Pinilla, 2005). Researchers who have tested the effects of exercise on BDNF generally examine voluntary wheel running in rodents and demonstrate an impact on BDNF in the hippocampus (Berchtold *et al.*, 2005; Neeper *et al.*, 1996; Widenfalk *et al.*, 1999). Importantly, findings also suggest that the presence of oestrogen (Berchtold *et al.*, 2001; Cotman and Engesser-Cesar, 2002) and the use of anti-depressants (Russo-Neustadt *et al.*, 1999, 2000, 2001) moderate this relationship.

Recent research with humans suggests that serum levels of BDNF are sensitive to an acute bout of exercise (Ferris *et al.*, 2007; Gold *et al.*, 2003) and that the increase in BDNF is positively related to the intensity of the exercise (Ferris *et al.*, 2007). Because BDNF is able to cross the blood–brain barrier (Pan *et al.*, 1998; Pan and Kastin, 2004), the implication is that these increases in serum levels of BDNF are indicative of increases in BDNF in the brain and, hence, have long-term implications for brain health and cognitive performance.

12.3 Moderators of the relationship

Importantly, researchers have also begun to look at the potential for the effects of physical activity on cognition to be influenced by moderators such as genotype. The only genotype that has been studied to date is apolipoprotein E (ApoE), which is a common susceptibility gene for Alzheimer's disease (AD) (Farrer *et al.*, 1997; Myers *et al.*, 1996). Individuals who have two copies of the ApoE-ε4 allele are at greatest risk for AD, followed by individuals with one copy of the ApoE-ε4 allele (whose susceptibility varies depending on whether the other allele is ε2 or ε3) and followed by those who are noncarriers. Results from the research in this area highlight our lack of understanding of differences in the relationship as a function of whether we assess physical activity or aerobic fitness. Findings from prospective studies have demonstrated conflicting results with Podewils *et al.* (2005) finding that physical activity benefits the cognitive functioning of ApoE-ε4 noncarriers and has no effect for ApoE-ε4 carriers, while Schuit *et al.* (2001) and Rovio *et al.* (2005) found that physical activity benefits cognitive functioning for ApoE-ε4 carriers but has no effect for ApoE-ε4 noncarriers. Consistent with Schuit *et al.* and Rovio *et al.*, Etnier *et al.* (2007), testing the relationship between aerobic fitness and cognition, found that aerobic fitness was predictive of better cognitive performance for the ApoE-ε4 hymozygotes, but had no effect for ApoE-ε4 heterozygotes or noncarriers. This finding that the relationship between aerobic fitness and cognitive performance is moderated by ApoE is important for two reasons. First, in conjunction with the Schuit *et al.* and Rovio *et al.* findings, it suggests that physical activity might serve to mitigate the effects of ApoE-ε4 on the experience of AD. Second, it suggests a possible explanation for the previously described lack of consensus of the empirical studies examining the effects of aerobic fitness on cognitive performance in the general population of older adults.

12.4 Practical conclusions

Practical conclusions that can be drawn from this rapidly expanding area of research remain necessarily vague because of our lack of understanding of mechanisms, and our current inability to establish dose–response effects. However, the weight of the evidence suggests that older adults who have maintained a lifestyle of physical activity

perform better cognitively than their inactive counterparts and maintain their cognitive abilities with advancing age. Evidence further supports a causal relationship between physical activity and cognition with an average effect size of approximately $^1/_2$ a standard deviation. Thus, an obvious recommendation is that older adults should be physically active to protect their cognitive abilities and that currently sedentary older adults can experience cognitive benefits as a result of participating in an aerobic exercise programme. However, we are not yet able to provide answers to the logical follow-up questions as to what type of exercise should be performed, at what intensity, for how many days per week and for how many weeks.

12.5 Challenges

Conducting research in this area is both daunting and exciting. It is made daunting by the complexity of the relationship, by measurement issues and by experimental design quandaries. As scientists, we frequently use reductionistic methods to make our hypotheses testable and our empirical studies manageable. However, these reductionistic methods may be oversimplifying the research question to the extent that we are not advancing knowledge as rapidly as we could. For example, physical activity appears to have effects on a variety of neurotrophic factors and on cerebral structure and function. In addition, physical activity has been demonstrated to impact other mental health variables that might logically themselves be predictive of cognitive performance. These include variables such as depression (Craft and Landers, 1998; Lawlor and Hopker, 2001; North *et al.*, 1990), anxiety (Petruzzello *et al.*, 1991), sleep (Driver and Taylor, 2000; Kubitz *et al.*, 1996) and affect (Arent *et al.*, 2000). Many times we either ignore or control (either statistically or methodologically) the majority of these potentially relevant variables as we focus on one variable or a couple of variables as the primary outcome variables in our research. As such, it is my opinion that we might be missing important interactive relationships between these potential mechanisms and mediators that would have implications for the prescription of physical activity to benefit cognitive performance.

This area of research is further complicated by measurement issues. Physical activity is defined as 'bodily movement that is produced by the contraction of skeletal muscle and that substantially increases energy expenditure' (American College of Sports Medicine, 2000, p. 4). The measurement of physical activity is particularly challenging because it is performed in free-living situations and involves a nearly infinite number of different types of activities. The extant literature in this area has been hampered by a nearly exclusive focus on self-report measures of physical activity and by the failure of scientists to use existing measures of physical activity that have established psychometrics.

The measurement of cognitive performance is also challenging. Indicative of this challenge is the listing by Lezak, Howieson and Loring (2004) of approximately 400 measures that have been designed to assess various aspects of cognitive performance. The extant literature reflects enormous variety in the cognitive measures that are

used to assess the outcome and the particular measure selected can have an impact on the results of the study (as evidenced by the findings of the Colcombe and Kramer [2003] meta-analysis that was previously discussed). Even the construct of executive function, which is so popularly used in recent cognitive research, is not free from debate regarding its measurement (Alvarez and Emory, 2006; Salthouse *et al.*, 2003) and its link to frontal lobe functioning (Alvarez and Emory, 2006).

Lastly, and perhaps most daunting, are problems of cohort effects which are not easily overcome. Cohort effects refer to the fact that the relationship between physical activity and cognitive performance might differ as a function of birth year. Clearly, the cognitive reserve hypothesis provides an example of why this could be a very real issue. That is, if cognitive reserves are developed through exposure to a stimulating environment, perhaps there are real differences in the level of stimulation provided by the environment of a child born, for example, in 1940 as compared to a child born in 1980. If this is the case, then it is certainly possible that the beneficial effects of physical activity on cognitive performance might be evidenced by one of these birth cohorts but not by the other. This would then suggest that the beneficial effects of physical activity on cognitive performance are not immutable and that research using different birth cohorts might find differing results.

12.6 Future research

Researchers in this area should focus on enhancing our understanding of the mechanisms responsible for the relationship between physical activity and cognition; should design studies to improve our understanding of dose-response relationships; and should continue to explore how moderators (like, but not limited to, ApoE) might influence the relationship. In addition, it is important for researchers to conduct theory-driven research so that we move towards the development of a cohesive body of research that provides clear evidence relative to the potential efficacy of physical activity as a behavioural means for protecting and/or enhancing cognitive performance.

13

Exercise and cognition in children

Catherine L. Davis and Kate Lambourne

The idea that physical activity promotes mental acuity, or *mens sana in corpore sano*, is an ancient one. Physical activity has been prescribed to enhance health and vigour, and health status has been thought to have an impact on a child's ability to learn. This type of thinking influenced the development of the modern physical education system in the United States and also in many other countries. Physical education has been a part of the educational system since its inception, becoming mandated in many states toward the latter part of the nineteenth century. During the 1900s, competition with European schools led to an even greater emphasis on US children's physical fitness. In the 1950s, the Presidential Fitness Test was instituted to assess fitness level in schools. There was a widespread importance placed on training the body as well as the mind.

More recently, pressure on schools to improve academic achievement (i.e. The No Child Left Behind Act of 2001) has resulted in cuts in the time and resources allocated to physical education (Allegrante, 2004; Kemper, 2003). This may have contributed to the high increase in overweight and obese children (Ogden *et al.*, 2006). Despite the longstanding belief that a healthy body supports a healthy mind, the link between physical activity and cognition has only recently been demonstrated in adults and children. The impact of physical education on children's cognition and academic achievement remains speculative.

13.1 Definition of terms

Physical activity and exercise

'Physical activity is defined as any bodily movement produced by skeletal muscles that results in energy expenditure. Exercise is a sub-set of physical activity that is

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planned, structured and repetitive and has as a final or an intermediate objective the improvement or maintenance of physical fitness' (Caspersen, Powell and Christenson, 1985). Physical training is a programme of regular exercise designed to improve physical fitness. In this chapter, the term 'exercise' refers to regular (chronic) physical activity or physical training, rather than an acute bout of exercise.

Cognition

The term 'cognition' is Latin for 'to know' and is typically used to describe human information processing and memory. Cognition has to do with how individuals understand and make sense of internal and external phenomena. It involves such processes as attention, perception and problem solving. Cognitive processing includes both basic information processing and executive control. The former 'bottom up' processes include encoding and stimulus evaluation, whereas the latter 'top down' processes include planning, strategy use and organization of goal-directed actions.

This chapter will discuss the literature that has examined exercise and cognition in adults and children, outline a recent experimental study of this relationship in children, discuss potential mechanisms for such an effect and provide recommendations for future research. It is meant to describe the current state of the literature and serve as guidance to those wishing to do research in this area.

13.2 Literature review

Our understanding of the exercise–cognition relationship has advanced significantly due to recent work conducted with older adults. This work generated the executive function hypothesis.

Exercise and cognition research in adults

The evidence for the relationship between exercise and cognition has developed rapidly in the past decade. Early reviews of the research in adults and children (Folkins and Sime, 1981; Plante and Rodin, 1990; Tomporowski and Ellis, 1986) concluded that there was little support for a significant influence of exercise on cognition. A quantitative meta-analysis (Etnier *et al.*, 1997) revealed that the effects of exercise on cognition were positive but small. The authors concluded that the effects were limited to the facilitation of response speed and that exercise had little influence over more complex, controlled processes. Prospective cohort studies conducted with older adults suggest that long-term, regular physical activity, such as walking, may reduce the risk of dementia (Larson *et al.*, 2006; Singh-Manoux *et al.*, 2005; Weuve *et al.*, 2004).

Executive function hypothesis

The executive function hypothesis is the idea that the benefits of exercise on cognition are specific to the processes that require cognitive control (Hall, Smith and Keele, 2001; Kramer *et al.*, 1999). Executive function is the supervisory control of cognitive processes. This includes goal-setting, self-monitoring, self-control (i.e. inhibition), planning and carrying out activity sequences that make up goal-directed behaviour, use of strategies and allocation of attention and memory (Eslinger, 1996; Lezak, Howieson and Loring, 2004). Thus, processes such as planning and inhibition are posited to be enhanced more by exercise and fitness than tasks that do not require effortful processing.

The earliest experimental evidence for the executive function hypothesis was a randomized study of regular exercise in older adults (Kramer *et al.*, 1999). The authors pointed out that there is a differential, age-related decline in cognitive processes, where the largest declines are seen in the frontal lobes and the executive functions that are associated with these areas. In this study, sedentary individuals over the age of 60 years were randomly assigned to a 6 month long aerobic exercise or control condition. The aerobic exercise consisted of brisk walking for 45 minutes, three days per week. The control condition was stretching and toning. Aerobic exercise significantly improved performance on executive functioning tasks that rely on the prefrontal cortex circuitry.

A review published in 2001 made a distinction between the effects of exercise on executive versus nonexecutive cognitive function (Hall, Smith and Keele, 2001). It was concluded that in older adults, aerobic exercise preferentially benefited executive function. A subsequent meta-analysis examined 18 experimental studies, which included sedentary older adults, and found that regular exercise resulted in cognitive benefits (Colcombe and Kramer, 2003). The strongest effects were found for tests of executive functions that involved planning, inhibition and scheduling of mental processes. The researchers concluded that their results were support for a causal relationship between exercise training and cognition, and that this relationship was strongest when the tasks used to assess cognition tapped into executive function.

Mechanistic evidence supporting the executive function hypothesis was obtained in a study that extended these results to show concomitant changes in brain function in the prefrontal cortex circuitry (Colcombe *et al.*, 2004). The prefrontal cortex circuitry is the locus of executive function (Lezak, Howieson and Loring, 2004). In this study, the researchers made a quasi-experimental comparison of highly fit and unfit older adults with regard to brain activity in the regions that support executive control processes. This paper also reported a randomized controlled trial that tested the effect of 6 months aerobic exercise (walking three times a week) on brain activity while performing an executive function task (flanker task) (Eriksen and Eriksen, 1974). Along with improvements on performance of executive function tasks in the active group, differences in brain activity were found in both the quasi-experimental and experimental comparisons. The brain areas implicated include the middle

frontal gyrus, the superior frontal gyrus, the superior and inferior parietal lobules, and the anterior cingulate cortex.

These publications constitute a turning point in this line of research. Whereas earlier studies had provided little support for an effect of exercise on cognition, it became apparent that exercisers improved more than nonactive controls on a variety of cognitive processes, with the largest effects on measures of executive processes. Following these publications, the executive function hypothesis began to gain support. The question remained, however, whether or not the benefit of exercise on cognition, and executive function in particular, occurs in children.

Exercise and cognition research in children

Executive function in children

Executive function develops during childhood (Brocki and Bohlin, 2004; Klenberg, Korkman and Lahti-Nuuttila, 2001; Lehto *et al.*, 2003; Levin *et al.*, 1991). It is crucial for adaptive behaviour and child development (Lyon and Krasnegor, 1996). Successful goal-oriented behaviours often require a child to suppress behaviours, which may lead the child to gain immediate reward but at the cost of reducing the possibility of the child's later attainment of goal-oriented rewards (i.e. delayed gratification) (Mischel, Shoda and Rodriguez, 1989). The capacity to self-regulate behaviour is important for a child's readiness for elementary school (Blair, 2002). Attention deficit disorder, characterized by lack of control of attention and impulsive behaviour, has been explained in terms of ineffective executive function processing (Barkley, 1997). Executive function in early childhood tracks into adolescence. Pre-schoolers' ability to delay gratification, and the attentional allocation strategy the more patient ones use to do so (i.e. avoid attending to temptations), predicted performance in adolescence on an inhibitory task (Eigsti *et al.*, 2006). Several recent reports have focused on the operationalization of children's executive function (Blair, Zelazo and Greenberg, 2005; Carlson, 2005; Hongwanishkul *et al.*, 2005) and its underlying neural structures (Kain and Perner, 2005).

Executive function and achievement

Executive function has been positively related to achievement (St Clair-Thompson and Gathercole, 2006). Specifically, cognitive shifting, inhibition and working memory are related to mathematics strategies and mathematics scores (Bull, Johnston and Roy, 1999; Bull and Scerif, 2001; Espy *et al.*, 2004; St Clair-Thompson and Gathercole, 2006), and with English, mathematics and science scores (St Clair-Thompson and Gathercole, 2006). Executive function is related to writing skills (Hooper *et al.*, 2002; St Clair-Thompson and Gathercole, 2006). Inhibition is related to reading (Gernsbacher, 1993) and vocabulary learning (Dempster and Cooney, 1982). Pre-schoolers with good executive function skills had higher mathematics and literacy scores in kindergarten, controlling for general intelligence, suggesting that executive function may play a causal role (Blair and Razza, 2007).

Exercise and children's cognition

There is some experimental evidence that exercise might improve children's cognition (Brown, 1967; Hinkle, Tuckman and Sampson, 1993; Ismail, 1967; Tuckman and Hinkle, 1986). However, other studies have had less encouraging results (Corder, 1966; Zervas, Danis and Klissouras, 1991). A meta-analysis of the published and unpublished literature found an effect size of $d = 0.32$, but the authors cautioned that the available evidence did not support a causal relationship between regular exercise and improved cognition (Sibley and Etnier, 2003). Several of these studies were conducted on children with developmental disabilities. Another limitation of this experimental literature is that many of the studies did not describe the physical activity in adequate detail (Tomporowski *et al.*, 2008). Some may have failed to detect an effect due to an inadequate experimental stimulus (Gutin and Owens, 1996).

In light of the evidence of the effect of exercise on executive function in older people, we hypothesized that the mixed findings in children may be explained by the fact that the cognitive tests employed did not provide sensitive measures of executive function (Lezak, Howieson and Loring, 2004). The studies which employed global measures of cognition, for example intelligence quotient (IQ) tests), consistently failed to find any effect of exercise training. Conversely, studies that employed process-specific tests designed to measure components of mental functioning reported positive effects (Tomporowski *et al.*, 2008). Tests of creativity, which may be considered to reflect executive function, showed benefits (Hinkle, Tuckman and Sampson, 1993; Tuckman and Hinkle, 1986). One of the tests that showed exercise benefits, the Alternate Uses Test, is considered a neuropsychological test of executive function (Lezak, Howieson and Loring, 2004; Tuckman and Hinkle, 1986).

Exercise and academic achievement

The impact of exercise on children's cognition implies a link to academic performance. Few experimental studies address this question. Population studies provide evidence that inactivity and excess weight are associated with poor academic achievement. Cross-sectional and longitudinal studies performed in the Americas, Europe and Australia provide clear evidence for the association of inactivity and obesity with poorer academic performance (Datar, Sturm and Magnabosco, 2004; Dwyer *et al.*, 2001; Falkner *et al.*, 2001; Laitinen *et al.*, 2002; Mikkila *et al.*, 2003; Mo-suwan *et al.*, 1999; Sigfúsdóttir, Kristjánsson and Allegrante, 2007; Taras and Potts-Datema, 2005; Tershakovec, Weller and Gallagher, 1994). This does not indicate a causal role for being overweight, however. Fitness has also been related to achievement. A large 2004 study demonstrated a strong positive relationship between children's 'Fitnessgram' scores and performance on a state-wide achievement test (California Department of Education, 2005). A recent study found aerobic fitness predicted better achievement in 3rd and 5th graders (Castelli *et al.*, 2007). Overweight and poor fitness are markers of a sedentary lifestyle, therefore physical activity may be the active ingredient behind these associations. For example, a recent

cross-sectional study verified the association of being overweight with poor achievement, but this appeared to be explained by fatness and other health risk measures (Cottrell, Northrup and Wittberg, 2007).

A recent prospective study showed that girls, but not boys, who spent more than an hour per week in physical education had an advantage in mathematics and reading achievement (Carlson *et al.*, 2008). However, few randomized trials have been conducted to examine the effect of physical activity on achievement. Prior to the Medical College of Georgia (MCG) study, to be described below, only one randomized study of exercise had found improvements on an objective measure of children's academic achievement (Ismail, 1967). While there was no difference on an intelligence test, the aerobically trained (8 months) children had an advantage over the untrained children on the Stanford Achievement Test. In contrast, Coe and colleagues (Coe *et al.*, 2006) failed to detect an improvement in academic achievement following a semester of vigorous physical activity, however the exercise was associated with higher class grades. Dwyer and colleagues (Dwyer *et al.*, 1983) also failed to find an effect of physical activity on standardized tests of academic performance after assigning schools to experimental and control conditions. Interpretation of the results of the remaining studies is difficult due to methodological limitations. The Sports, Play and Active Recreation for Kids project (Sallis *et al.*, 1999) showed that despite spending twice as much time in physical education, children in a more active physical education condition performed just as well on an academic achievement test as those who were less active. However, this landmark study suffered from high drop-out rates and subject selection bias. Another important study, the Three Rivers Project (Shephard *et al.*, 1984) used teacher-assigned grades as the primary outcome measure instead of an objective standardized test.

Until recently, the strongest statement one could make regarding the effect of physical activity on achievement is that at least it does not worsen achievement, even when it takes away classroom time (Shephard, 1997). This is changing. One, as yet unpublished study, showed that regular, brief bouts of physical activity in the classroom (≥ 75 min wk^{-1} over 3 years), incorporating lesson material (e.g. hop-scotch as a spelling lesson), benefited achievement (Donnelly *et al.*, 2007; DaBose *et al.*, 2008). A field study in Naperville IL, which has not been peer-reviewed, showed improvements in achievement after a vigorous physical education programme was instituted (Ratey and Hagerman, 2008).

13.3 The Medical College of Georgia study

Georgia Prevention Institute

The Georgia Prevention Institute (GPI) is a research division of the Department of Pediatrics at MCG. Pediatric cardiologist Dr William Strong and educational psychologist Dr Maurice Levy collaborated on one of the first Preventive Cardiology Academic Awards from the National Institutes of Health (NIH). This project, the

Students for Community Involvement, taught medical students about preventive cardiology by having them teach the material in 6th grade (11–12 year olds) classrooms. Thus began the relationship which allowed MCG researchers to recruit child research participants from local schools. In 1981, the Board of Regents established the Georgia Institute for the Prevention of Human Disease and Accidents (now known as the GPI). In 1985, Drs Strong, Levy and Treiber, a clinical child psychologist, received a NIH grant to study the relationship of childhood diet and exercise to future heart disease, the Survey of Children's Activity and Nutrition (SCAN). Participants initially recruited as early as pre-school have been followed ever since in prospective studies of cardiovascular risk development. Dr Bernard Gutin joined the GPI in 1991, after retiring from Teachers College at Columbia, where he had participated in a SCAN project. At the GPI, he conducted several clinical trials examining the health benefits of exercise for obese children, utilizing an aerobic exercise programme with heart rate monitoring and incentives for reaching a target heart rate (Gutin, Barbeau and Yin, 2004; Gutin and Owens, 1999; Gutin *et al.*, 1999). This method was applied in the MCG study of exercise and cognition described below. Current recommendations for children (at least 1 hr day^{-1} of moderate to vigorous physical activity) are based largely on these controlled studies with 40 min day^{-1} of vigorous activity, since in free-living situations children require longer than 40 min to accrue so much activity (Strong *et al.*, 2005). Today, an interdisciplinary faculty including cardiology, clinical psychology, exercise science, genetic epidemiology, molecular genetics, nursing and physiology conduct mechanistic and prevention studies of cardiovascular risk, funded mainly by the NIH and the American Heart Association.

Experimental hypotheses

To address the executive function hypothesis in children, researchers from the GPI (CLD) and the University of Georgia (Dr Tomporowski) conducted an ancillary study on cognition and achievement outcomes, as part of a large-scale clinical trial to study dose–response effects of exercise on diabetes risk in overweight children (NIH DK 60692). The ancillary study was initially funded by the state and intramural grants from MCG and UGA, and then supported by a federal grant (NIH DK 70922). The study focused on overweight children because their overweight status reflected a sedentary lifestyle. Therefore, the effects of regular, vigorous physical activity were likely to be greater in this population.

The primary hypothesis was that sedentary, overweight children assigned to exercise would improve more than children in a control condition on executive function but not other cognitive processes. Dose–response was a secondary hypothesis. Effects on achievement and classroom behaviour were explored. Possible moderation by race, gender and socioeconomic status (i.e. mothers' education) was tested. A pilot study examining brain function as a possible mechanism of cognitive change was conducted in a sub-set of the sample.

Classroom behaviour was examined because exercise-induced improvements in classroom behaviour (e.g. attentiveness) might be responsible for improvements in

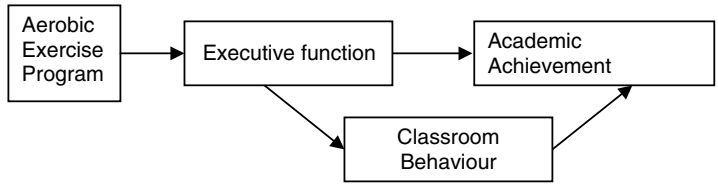

Figure 13.1 Conceptual model for the Medical College of Georgia experiment.

achievement. Adverse effects of physical activity on children's classroom behaviour have been hypothesized (that it would fatigue children or hyperstimulate them). On the other hand, a study examining the impact of recess (break or playtime) on classroom behaviours revealed that children worked more on task and fidgeted less on days they were offered a recess period (Jarrett *et al.*, 1998). The conceptual model for the experiment is shown in Figure 13.1.

Methods

Participants

Two hundred and twenty-two sedentary, overweight (body mass index $\geq$ 85th percentile), but otherwise healthy, 7–11 year-old children were recruited from local schools, completed baseline testing for the parent study (DK60692) and were randomized to a low-dose (20 min day^{-1} exercise), high-dose (40 min day^{-1} exercise) or control condition. The exercise conditions were equivalent in intensity but differed only in duration and, therefore, energy expenditure. Due to limited funding early in the trial, not all children completed the cognitive evaluations; 172 of the children randomized completed pre-test cognitive evaluations. One child developed a severe psychiatric disorder and was dropped from the study. One hundred and sixty-three completed cognitive assessments at baseline and post-test (mean age 9.3 ± 1.0 years, body mass index z-score $= 2.1 \pm 0.4$, 56% female, 63% black). Children were recruited and intervened upon in cohorts of about 40. Because attention deficit disorder is a common diagnosis, in order to maximize generalizability, 11 children taking medication for attention-deficit disorder were included and took their medication as usual.

Intervention

The exercise sessions were held on school day afternoons in the research gymnasium and instructed by trained research staff. The children assigned to the exercise programme were provided free transportation via school bus to the research gymnasium. Healthy snacks (e.g. fruit, crackers) were provided prior to the exercise. Polar heart rate monitors (S610i; Polar Electro, Oy, Finland) were used to monitor intensity and incentivize adherence to the exercise dose. The emphasis was on intensity, enjoyment and safety, not competition nor the enhancement of skills; therefore,

activities were selected based on ease of comprehension, fun and ability to elicit a heart rate greater than 150 bpm. Examples of these activities include running games, jump rope, basketball and soccer (Gutin *et al.*, 1999; Turner and Turner, 2000). Twenty minute bouts of intermittent, vigorous exercise were carried out in a fashion consistent with guidelines for children, in short bursts of intense physical activity interspersed with lower intensity activity (recovery) (Bailey *et al.*, 1995; Corbin and Pangrazi, 2004). The two exercise groups exercised in the same gymnasium. After the first 20 min bout, the low dose group was escorted to a separate room where they engaged in supervised sedentary activities, while the high dose group completed a second 20 min bout. No tutoring was provided during this period. Each session began with a 5 min warm-up. Bouts ended with a cool-down. Those assigned to the exercise groups received 12.9 ± 1.6 weeks of the exercise programme between baseline and post-test. Children were invited to continue the programme after post-test to maintain the quality of the intervention and most did so.

The exercise programme was an enjoyable experience for the children. (The programme handbook is available on request.) A wide variety of games was used to elicit vigorous activity and maintain interest. We selected games based on children's preferences and the level of participation the games elicited. One popular game was Bumblebee Tag: three students or instructors are designated taggers, who carry foam pool noodles (stingers). Taggers attempt to sting as many participants as possible, within an allotted time period. This results in much running and gleeful shrieking. If a child gets stung, the child must freeze and do 15 jumping jacks to rejoin the game.

A token economy was used to encourage adherence to the exercise programme. Children were awarded points daily for attending at least 4 days per week and attaining an average heart rate > 150, with more points for higher heart rates. Nearly every child achieved this goal nearly every week. Points were redeemable weekly for small prizes (e.g. pencils, small toys). Daily points were lost for misbehaviour. Any child who refused to participate was marked absent. Children quickly learned to check their watches and do vigorous activity to keep their heart rate high enough to earn prizes. Rewarding children for reaching a heart rate target calibrates for their fitness level, since less fit children will reach a given heart rate at a lower level of activity. There is < 4 bpm difference in exact target heart rate ($70\% \times [220 - \text{age}]$) from 7 to 11, so we used a single target (150 bpm) for all. Average heart rates during the classes were 166 ± 7.6, or about 79% maximum heart rate, indicating vigorous activity. Average attendance was $85 \pm 13\%$ of available days. There were only three dropouts from the exercise programme. Thus, adherence goals were exceeded. Exercise intervention duration, attendance and average heart rate were similar for the low and high dose groups. Excellent retention (96%) was achieved. This lends confidence to the results, since there is not a question of what happened to a substantial proportion of enrolees and why they were lost to follow-up.

A lifestyle education course based on authoritative, publicly available materials (e.g. American Heart Association, American Diabetes Association, NIH, US Department of Agriculture) was provided monthly to all families enrolled in the

trial in order to maintain interest and contact with families assigned to the control group. Because this was offered to all families regardless of randomization, it is not relevant to the experimental comparison. Children, including siblings of enrolled children, were instructed in a separate room to allow tailoring of developmentally appropriate instructional material and activities, and reduce distraction for parents. Both the exercise programme and lifestyle classes were evaluated positively by participants.

Measurements

A standardized psychological battery assessed cognition and achievement at baseline and post-test. Most children (98%) were evaluated by the same tester, at the same time of day and in the same room at baseline and post-test. Testers were blind to the child's experimental condition. The Cognitive Assessment System (CAS) measures children's mental abilities defined on the basis of four interrelated cognitive processes: Planning, Attention, Simultaneous and Successive (Naglieri and Das, 1997). Each of the four scales is comprised of three sub-tests. Only the planning scale measures executive function (i.e. strategy generation and application, self-regulation, intentionality and utilization of knowledge; internal reliability $r = 0.88$). Thus, it was hypothesized that only the Planning scale would be influenced by exercise. The remaining scales measure other aspects of cognitive performance and, thus, can determine whether the effects of exercise in children are stronger for executive function than for other cognitive processes. The Attention tests require focused, selective cognitive activity and resistance to distraction (internal reliability $r = 0.88$). The Simultaneous sub-tests involve spatial and logical questions that contain nonverbal and verbal content (internal reliability $r = 0.93$). The Successive tasks require analysis or recall of stimuli arranged in sequence and formation of sounds in order (internal reliability $r = 0.93$). Children's academic achievement was measured using the Broad Reading and Broad Mathematics clusters of the Woodcock-Johnson Tests of Achievement III (McGrew and Woodcock, 2001). Parent and teacher reports of children's classroom behaviour were obtained (Conners, 1999). The means for cognitive and achievement scores fell in the normal range.

Statistical analyses

Analysis of covariance examined the effect of randomization on post-test scores, with race, gender, cohort and baseline scores as covariates. All children were encouraged to complete the post-test and were included in analyses, regardless of adherence to the exercise programme (i.e. an intent-to-treat analysis was conducted). A priori contrasts tested the dose–response hypothesis.

In the pilot study of brain function, children were scanned at baseline and post-test using functional magnetic resonance imaging (fMRI) to test whether changes in brain function (particularly in the frontal-parietal circuit) during an executive function task were caused by the exercise programme.

Results

The results of the MCG study provided strong evidence for a selective causal effect of aerobic exercise training on children's executive function (Davis *et al.*, 2007) and suggested a benefit in mathematics achievement (Davis *et al.*, under review). Effects on classroom behaviour did not reach significance. Preliminary evidence was provided for brain activation changes consistent with the executive function improvements.

Cognition

Analysis of the post-test CAS scores revealed selective effects on executive function, with group differences on the Planning scale only. There was a significant linear trend (indicating increasing benefit with an increasing dose of exercise, i.e. dose–response) ($p = 0.015$) on the planning sub-scale (Figure 13.2). No significant differences were found on the remaining scales (attention, successive and simultaneous) of the CAS. Thus, it confirmed the study hypothesis. No significant interactions of group with race, gender, age or mothers' education were detected, indicating that the results may be generalized across these factors.

CAS planning was related at baseline to fitness ($r = 0.25$, $p = 0.001$) and inversely related to fatness (BMI z-score $r = -0.20$, $p = 0.01$), percent fat ($r = -0.21$, $p < 0.01$) and waist ($r = -0.19$, $p = 0.015$). Changes in CAS planning, however, were unrelated

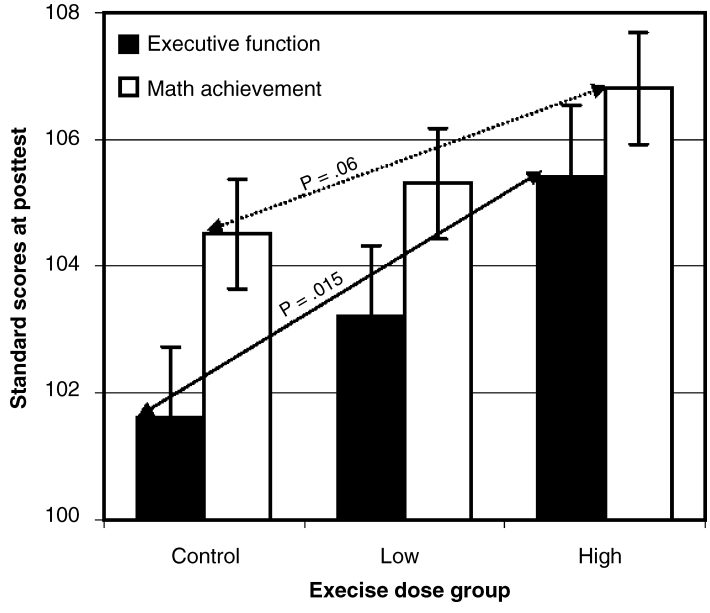

Figure 13.2 Cognitive and achievement results.

to changes in fatness or fitness (r from -0.02 to 0.05). This suggests that physical changes may not be responsible for the cognitive benefits.

Results were similar, excluding the 11 children treated for attention deficit disorder. This suggests that the children with this difficulty benefited as much as the other children. However, this group was too small to establish the effect in this population. Further studies are needed to determine whether and to what extent exercise enhances executive function in children with attention deficit disorder. If exercise can correct the executive function deficit thought to be the core dysfunction in attention deficit disorder, it may be a particularly efficacious treatment alone or in combination with pharmacotherapy.

Academic achievement

The results showed small but significant improvements in mathematics achievement but no effect on reading achievement. The linear trend approached significance for Broad Mathematics ($p = 0.06$, Figure 13.2), with a similar trend for a sub-test, Mathematics Fluency ($p = 0.05$). A contrast comparing both exercise groups to the control group showed significant improvement in Mathematics Fluency ($p = 0.01$). Planning scores were related to both mathematics (r 0.59–0.65, $p < 0.001$) and reading achievement (r 0.51–0.55, $p < 0.001$) at both baseline and post-test. Broad Mathematics changes were correlated with changes in CAS Planning ($r = 0.24$, $p = 0.005$).

These results are particularly interesting due to the fairly short length of the exercise programme, as well as the fact that academic achievement improved even though no academic instruction was provided. Academic achievement is difficult to change, even when the students are given lessons within the specific areas being measured, such as mathematics. Also of interest is the specificity of the effect on mathematics, but not reading scores. It may be that mathematics draws more on executive function processes than reading, which is a more automatic behaviour. For instance, successful completion of a mathematics problem requires the planned, controlled execution of steps, then checking of the result.

Classroom behaviour

Teacher ratings of the children's behaviour improved in response to the exercise, although these results did not reach statistical significance. Children in the exercise conditions had lower adjusted post-test scores than controls on their Cognitive problems/inattention (51.4 versus 53.3, $p = 0.07$) and Attention Deficit Hyperactivity Disorder (ADHD) scales (53.5 versus 55.8, $p = 0.09$). High scores on the cognitive Problems/Inattention scale suggest problems in the areas of attention, work organization, completion of tasks and schoolwork, and concentration on tasks that require continuous mental effort. The ADHD scale is used as a screen for this clinical condition. No group differences were observed on other teacher rating scales (Oppositional Defiance, Hyperactivity) or on the Conners' Parent Rating Scale. (This belies any potential bias due to teachers' expectation that exercise would help).

These exploratory results are consistent with the CAS results showing a beneficial effect of aerobic exercise on cognitive functioning, and may suggest that vigorous physical activity programmes could have a beneficial effect in a classroom setting. Lack of a dose–response effect suggests, however, that it may be the behavioural structure of the programme (e.g. rewards for good behaviour) rather than exercise per se that is responsible for behavioural improvements. Teacher ratings on the Cognitive Problems/Inattention scale were related to mathematics and reading achievement at pre- and post-test (r −0.46 to −0.50, $p < 0.01$).

Brain function

Brain scans in a sub-set of the children provided some mechanistic evidence to complement the psychological evaluations. During a task that requires inhibition of a glance (anti-saccade [McDowell *et al.*, 2002]), the exercise group showed increased bilateral prefrontal cortex activity ($p = 0.04$) and decreased activity in the bilateral posterior parietal cortex ($p = 0.03$) compared to controls. This is consistent with studies in adults (Colcombe *et al.*, 2004) and with the observed benefit to a psychometric measure of executive function. Exercise may have increased prefrontal cortex activity during anti-saccades, which resulted in decreased need for recruitment of the attentional resources mediated by posterior parietal activity. Alternatively, the prefrontal cortex may have suppressed parietal regions associated with the visual spatial processing in order to reduce the probability of an error being generated (Clementz *et al.*, 2007). This increased prefrontal cortex activity during anti-saccades may reflect faster development of cognitive control in the exercised children. Studies using executive function tasks have shown that recruitment of performance-related prefrontal cortex areas increase with age, while unrelated areas show decreased activity (Casey *et al.*, 2004; Casey *et al.*, 2005). Thus, children in the exercise group who exhibited increased prefrontal cortex activity during an inhibitory task may have developed more executive function capacity.

Conclusions and implications

The experimental data obtained from the MCG study offer strong evidence that exercise can improve cognition in dose–response fashion among sedentary, overweight children, and suggest effects on school performance and classroom behaviour. The improvement of mathematics achievement is remarkable, given that no academic instruction was provided. The exercise group assignment was randomized and psychometric outcome evaluations blinded, minimizing potential bias or confounding.

At a time when a greater emphasis is being placed on preparing children to take standardized tests, these results should give school administrators reason to consider investing in quality physical education and vigorous activity programmes, even at the expense of time spent in the classroom. Not only will this not harm performance in school, it may improve it. Small benefits were detected with 20 min day^{-1} of vigorous

physical activity. Achieving this in physical education is possible but would require increased time for daily physical education and optimization of the curriculum to promote vigorous activity (Sallis *et al.*, 1997). Incorporating 40 min day^{-1} of vigorous activity to attain the greater cognitive benefits we observed will require additional programmes that are available to children of all skill levels. After-school programmes would allow time for academic enrichment along with vigorous physical activity and would meet the need of many families for a safe, constructive environment for children while parents are working.

13.4 Potential mechanisms

Despite the number of studies that have examined the influence of physical activity and fitness on cognitive function, relatively little is known about the mechanisms underlying this effect. Hypothesized mechanisms have been both biological and psychosocial. The two are not mutually exclusive: psychosocial explanations may also involve biological pathways.

Psychosocial mechanisms

It is possible that exercise exerts its influence indirectly via psychological mechanisms rather than directly through physiological changes that accompany physical activity. Attention from adults and peers in the context of an after-school programme could be an active ingredient that caused mental changes in the children. Learned improvements in self-control fostered by the token economy, or social skills learned through interacting with peers may also have contributed to the executive function benefits. However, since children assigned to either the low or high dose of exercise spent equal time with staff and peers in a structured environment, these cannot account for the dose–response pattern of findings. Nonetheless, future studies comparing an exercise programme to a nonexercise attention control condition are needed to isolate the effects of exercise on children's cognition.

Social cognitive theory (e.g. self-efficacy) is an important theory for physical activity (Bandura, 2004; Motl *et al.*, 2002; Strauss *et al.*, 2001). The positive effects of exercise on participants' behaviour and cognition have been explained in terms of its impact on such psychological variables as self-concept, mastery and self-efficacy, which may reflect the same construct (Judge *et al.*, 2002). Exercise periods are seen as opportunities for children with poor histories of success to develop or re-establish positive self-perceptions and attributes. We detected dose–response improvements in self-worth and depressive symptoms due to the exercise programme (Hammack et al., under review). These changes may be due to, or might contribute to, cognitive changes. Alternatively, cognitive and other psychological benefits could be due to similar underlying physiological changes.

Research conducted by Pellegrini and colleagues (Pellegrini, Huberty and Jones, 1995; Pellegrini and Smith, 1998) led them to conclude that post-recess changes in

classroom behaviour and attention are due to the opportunity to take a break from the cognitive demands experienced in classroom settings. Unique to this distributed learning hypothesis is the prediction that the level of physical activity performed during the recess period is unrelated to subsequent behaviour. The dose–response benefit detected in the MCG study is not consistent with this hypothesis, since the low-dose group also took a break from academic demands during the time the high-dose group engaged in exercise.

While there is little evidence that regular exercise reduces anger, it is a typical component of clinical anger management programmes (Larkin and Zayfert, 1996). Children's anger expression was also influenced by the exercise programme. The children reported less 'anger out' (e.g. slamming doors or shouting at people) after the exercise programme, while children in the control group increased in this domain. Improved executive function (e.g. inhibition) may be an important contributor to the observed reduction in anger (Tkacz et al., 2008). The observed changes in self-reported anger expression may be due, in part, to the behavioural structure (e.g. rules against hitting) of the exercise programme. However, the significant relationship of fitness improvements, a direct result of the exercise programme, with lower post-test Anger Out scores suggests that the physical activity itself may have caused these benefits. Anger reduction due to exercise may be partly responsible for the cardiovascular benefits of an active lifestyle (Everson-Rose and Lewis, 2005).

Another possible psychosocial mechanism is the mental operations inherent in organized physical activities, such as tracking objects and coordinating body movements in space, and maintaining rules in memory. The exercise activities required the children to use basic cognitive processes such as attention, memory, reasoning and coordination of motor movement. For this reason, Brown (1967) hypothesized that the cognitive improvements found in that study were the result of the mental engagement that occurred during exercise.

The type of exercise task and/or the challenge placed on the learner may influence the effect of exercise on cognitive function. Research conducted with animals shows clear evidence for differential effects of task complexity on brain function (Black *et al.*, 1990). Rats involved in acrobatic exercise training developed new neural connections within the cerebellum, whereas rats whose exercise was simply running improved in cerebral blood flow. Thus, it may be the case that children who are involved in play and structured games that involve learning and group cooperation may adapt differently than children who are involved in individual physical activities that are performed in relative isolation, (e.g. treadmill running or cycling on a stationary ergometer) (Pellis and Pellis, 2007).

The theory of embodied cognition (Wilson, 2002) holds that cognition arises from bodily interactions with the environment, particularly movements. Children are posited to learn cause and effect through movements intended to reach a goal. This idea is particularly relevant for the exercise–cognition link in children. On a related note, the cerebellum appears to play a more important role in cognition and emotion than previously understood (Epstein *et al.*, 2007; Lee *et al.*, 2004; Luna *et al.*, 2001; Pillai *et al.*, 2004; Rapoport, van Reekum and Mayberg, 2000). This brings us to the

biological mechanisms that may be responsible for the benefits of exercise on cognition.

Biological mechanisms

From a physiological standpoint, it is plausible that exercise training promotes systemic change in blood, oxygen and glucose supplies to the brain, which will impact cognitive functioning (Dustman *et al.*, 1990; Hall, Smith and Keele, 2001; Shephard, 1997). However, acute increased blood flow to the brain during exercise or improved cardiorespiratory oxygen supply due to aerobic fitness have not been supported as the mechanism of the neural benefits of exercise. These hypotheses would suggest that effects would be similar in all areas of the brain; however, the limited evidence from human imaging studies suggests that changes in specific areas are observed while participants are engaged in tasks (e.g. increased activity in the dorsolateral prefrontal cortex) (Colcombe *et al.*, 2004). A recent meta-analysis found no support for aerobic fitness as a mediator of the effect of physical activity on human cognition (Etnier *et al.*, 2006).

In contrast, research from imaging studies suggests that in the human brain, the prefrontal circuitry (including parietal and anterior cingulate cortex) is selectively influenced by exercise (Colcombe *et al.*, 2004; Hillman, Erickson and Kramer, 2008). Imaging evidence has been provided of exercise-induced neurogenesis in young adults (Pereira *et al.*, 2007) and brain tissue loss associated with inactivity (Colcombe *et al.*, 2003). Electroencephalogram (EEG) studies provide another window into human cognition. One cross-sectional study showed that EEG parameters differ with fitness level in both young adults and older individuals (Dustman *et al.*, 1990), a second found that both age and activity level were associated with adults' neuroelectric responses (Hillman *et al.*, 2004) and a third found that fitness could not explain the age-related difference between young and older adults (Etnier and Landers, 1998). Faster responses and neuroelectric indices of better executive function in children have been associated cross-sectionally with fitness in children (Hillman, Castelli and Buck, 2005) and with physical activity in adults (Hillman *et al.*, 2004; Hillman *et al.*, 2006a, 2006b). No experimental effects of exercise on EEG measures are yet published.

The animal literature suggests a direct role of neural stimulation by exercise. A proposed model is presented in Figure 13.3. According to the neurotrophic stimulation hypothesis, improvements in cognition are the result of neurological parameters, such as capillary growth and density, and an increase in synaptic connections. Animal studies show that aerobic training increases brain-derived neurotrophic factor and other growth factors, leading to increased capillary blood supply to the cortex and growth of new neurons and synapses, resulting in better learning and performance (Churchill *et al.*, 2002; Cotman and Berchtold, 2002; Cotman, Berchtold and Christie, 2007; Dishman *et al.*, 2006; Lu and Chow, 1999; Neeper *et al.*, 1995; van Praag *et al.*, 1999).

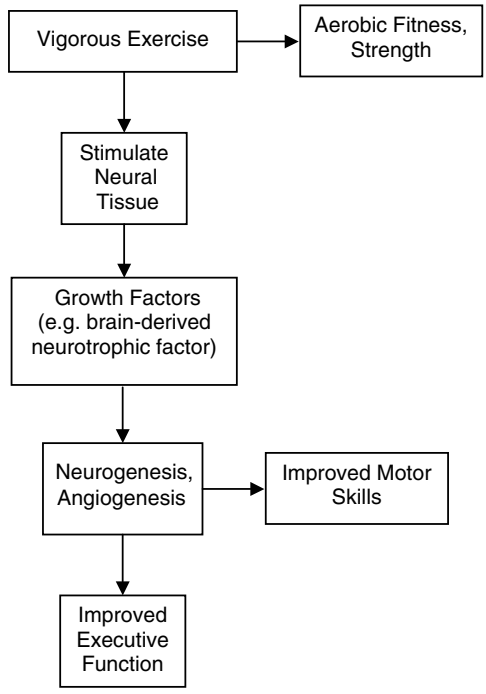

Figure 13.3 Model of exercise effects on executive function.

While not measured in the MCG study, serotonin (also known as 5-hydroxytryptamine) has a known association with exercise, depression and anger expression (Dishman *et al.*, 2006). In human adults, aggression has been shown to correlate negatively with central nervous system serotonergic activity (Coccaro, 1989). The human prefrontal cortex has a high density of serotonin receptors (Biver *et al.*, 1996). In rats, exercise has been shown to buffer stress by altering serotonin and noradrenaline brain systems (Greenwood *et al.*, 2003). Physical activity also enhances brain dopamine synthesis (Sutoo and Akiyama, 1996). The executive function circuits of the brain are rich in dopamine receptors (Dishman *et al.*, 2006; Swanson *et al.*, 2000).

The effect of exercise on the autonomic nervous system has been hypothesized as a mechanism for the benefits and/or adverse effects of exercise on cognition (Gutin, 1973). Heart rate variability, an index of parasympathetic function, has been associated with better executive function (Hansen, Johnsen and Thayer, 2003). A quasi-experimental study posited that increased vagal tone due to exercise, along with a benefit to executive function, might both be due to improved prefrontal cortex functioning (Hansen *et al.*, 2004). Parasympathetic activity has also been linked to psychopathy, a dysfunction of the prefrontal cortex circuitry (Birney *et al.*, 2007; Lezak, Howieson and Loring, 2004).

13.5 Summary and recommendations for future research

The MCG study provided the first experimental data in children that are consistent with the available data on the relationship between exercise and cognition in adults (Davis *et al.*, 2007; Davis *et al.*, In press; Tomporowski *et al.*, 2007b). It appeared that an aerobic exercise training programme had selective effects on cognitive function in overweight children. These effects were specific to changes in executive function. Functional MRI showed corresponding neural changes.

The results in healthy, overweight children are valuable but may not generalize to lean children, adolescents or children with clinically significant psychological problems such as attention deficit disorder, learning disabilities, depression or behaviour problems. Future research might also examine different types of physical activity. These differences have not been explored as potential mediators in the relationship between exercise and cognition.

The long-term effects of this type of intervention also remain to be determined. Although the duration of the intervention in the MCG study was longer than many in the literature, it is unknown whether a longer duration would provide more benefit. It also remains to be investigated whether the effects last after ceasing the intervention or dissipate like so many other benefits of physical activity. By improving cognition and learning early in life, physical activity may influence the trajectory of a child's development.

Quality of measurement directly affects the ability of a study to detect relationships. One of the challenges with this line of research is the difficulty in measuring children's physical activity levels. The relative ease of measuring body weight explains the comparatively vast literature on weight status, while physical activity has been understudied. Because children typically engage in short, intermittent bouts of intense activity, it can be difficult to reliably capture them (Bailey *et al.*, 1995). Furthermore, it may be difficult to operationally define what can be considered physical activity. Physical activity is typically defined in terms of frequency, duration and intensity. Instruments that can be used to measure physical activity behaviour in children include self-report instruments, direct observation, heart rate monitors, activity monitors such as pedometers or accelerometers, doubly-labelled water, indirect calorimetry and proxy measures such as time spent outdoors. Inactivity is sometimes considered the opposite of physical activity but appears to be an independent construct (Gordon-Larsen, McMurray and Popkin, 1999). The selection of an appropriate instrument depends on the research question at hand (Welk *et al.*, 2000).

Measurement of cognition is also challenging. Reliance on broad measures such as IQ tests masked the effects of exercise on children's executive function in early studies. Neuropsychological measures offer an appealing alternative. However, since they have often been normed on only a small population of brain-injured patients, they generally suffer from poor reliability (Rabbitt, 1997). Well-validated measures of executive function are now available.

As previously mentioned, relatively little is known about the mechanisms behind the changes in cognitive function that occur as a result of exercise. The MCG study made strides toward this goal by obtaining the fMRI data, but more research is certainly needed in this area. In conclusion, much remains to be learned about how social, psychological and biological factors may influence how physical activity alters children's mental processes. Research on these topics would lead to an elaborated model of the effects of exercise on cognition. Such a model might further clarify the bases for the inconsistencies in the literature, identify possible mechanisms underlying the role of exercise in cognition and direct interventions to more fruitful targets.

Given the many health benefits of physical activity, particularly in the context of a childhood obesity epidemic (Ogden *et al.*, 2006), it is sensible to pursue translation of this controlled experimental treatment to settings such as schools and community centres, staffed by teachers and fitness trainers rather than research staff, before all these questions have been answered. Demonstrating effectiveness and cost-effectiveness will be important to promote implementation of enjoyable, vigorous, physical activity programmes as widely as possible.

14

Chronic exercise and developmental disabilities

James Zagrodnik and Michael Horvat

In this chapter, we focus on the interaction between chronic exercise and cognition among those individuals with developmental disabilities. We will review the history of the literature investigating this topic, provide a summary of the studies' research findings and discuss any methodological issues among the studies. In addition, considerations for the direction of future research are included. Before a review of the literature on the topic, a section defining the terms of interest is provided to guide the reader on how the chapter was developed.

14.1 Defining terms

Developmental disability

Based on the most current classifications and definition of developmental disabilities, it is estimated that developmental disorders worldwide range from 30 to 63 per 10 000 (Fombonne, 2003; Chakrabarti and Fombonne, 2005). In 2002, over 405 000 people in the United States demonstrated at least one form of developmental disorder and were living in a publicly funded residence with nearly $27 billion dollars (Federal, State and private funds) being spent on community services (Hemp *et al.* 2002). It is important to note the 405 000 developmentally disabled individuals reported were recognized because they lived in some form of public assisted housing. This number does not include the developmental disabled individuals living in privately funded institutions or in a private residence with parents or family and thus is, at best, an underestimate of the number of developmentally disabled individuals in the US.

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The term 'developmental disability' is more an umbrella term for at least 21 differentiated developmental disabilities. These 21 identifiable developmental disorders include both well known (i.e. cerebral palsy, spina bifida, mental retardation, Down syndrome, autism and attention-deficit disorders) and more obscure (i.e. pediatric dysphasia, Williams' syndrome, dyscalculia) disorders. In addition, visual impairments, hearing loss, Tourette's syndrome and epilepsy are classified as developmental disorders. It is apparent that there is a wide spectrum of developmental disabilities branching across motor functioning difficulties, cognitive difficulties, language and communication difficulties, and learning difficulties.

The observation of developmental disorders in children is not new. Hooper, Hynd and Mattison (1992) stated that 'case descriptions of children with unusual but fairly specific learning profiles were presented in the 1800s' (p. 2). The Congressional definition can be traced to the Mental Retardation Facilities and Community Mental Health Centers Construction Act of 1963. This definition has undergone several additions, tinkering and restructuring as developmental disabilities have become better understood and examined. The most current Congressional definition of developmental disabilities comes from Section 102 (8) of the Developmental Disabilities Assistance and Bill of Rights Act of 2000 as:

(a) In general:

A severe, chronic disability of an individual that –

(1) is attributable to a mental or physical impairment, or combination of mental and physical impairments;

(2) is manifested before the individual attains age 22 years;

(3) is likely to continue indefinitely;

(4) results in substantial functional limitations in three or more of the following areas of major life activity:

(i) self-care;

(ii) receptive and expressive language;

(iii) learning;

(iv) mobility;

(v) self-direction;

(vi) capacity for independent living;

(vii) economic self-sufficiency;

(viii) reflects the individual's need for a combination and sequence of special, interdisciplinary or generic services, individualized supports or other forms of assistance that are of lifelong or extended duration and are individually planned and coordinated.

(b) In infants and young children:

> An individual from birth to age 9 years inclusive, who has a substantial developmental delay or specific congenital or acquired condition, may be considered to have a developmental disability without meeting three or more of the criteria described in clauses (I) through (V) of subparagraph (A) if the individual, without services and supports, has a high probability of meeting those criteria later in life.

Since many research investigations are backed by governmental agencies, the Congressional definition is frequently used to define the populations of interest. For the purposes of this chapter, the Congressional definition was selected, with the understanding that slight changes in the definition have occurred since 1963. While reviewing articles involving developmental disabilities, the time frame of investigation was considered as well as the Congressional definition of developmental disabilities at the time. For example, one study (Oliver, 1958) was found prior to legislative definition and was included based on the descriptions of the participants as most likely being mentally retarded. The term 'developmental disability' and individual diagnoses (i.e. autism, cerebral palsy, Down syndrome) were investigated during the literature search.

Chronic exercise

The definition of exercise is often used synonymously with physical activity. However, the distinction that exercise is planned and purposeful sets it apart from physical activity. Physical activity, in its most basic form, is any energy expenditure due to bodily movements. Today, many researchers often make clear distinctions within their studies if exercise and/or physical activity is/are being studied, however early (pre-1970) studies may have been more cavalier in their usage of the two terms. To avoid neglecting potential studies in this topic of research, the definition of chronic exercise, for the purposes of this chapter, was defined as the participation of movement activity for more than one day per week, for at least 20 min per session, with moderate levels of intensity. This broad definition was used to find as many investigations as possible to answer the question of interest without limiting findings to only laboratory studies, such as those findings from any physical activity, play activities and/or physical education interventions in the natural setting.

Cognition

The concept of cognition, as previous chapters have addressed, is rather abstract. Like the term 'developmental disabilities', cognition is an umbrella term which can compromise aspects of learning, reasoning, perception, intelligence, decision-making, planning, information processing, executive function and attention. With respect to this chapter, the literature search was primarily subjected to intelligence,

attention and information processing, however any facet involving cognition was investigated as key words for the literature search.

14.2 Research investigating the effects of exercise on cognition among the developmentally disabled

Research history

The first study to incorporate both aspects of exercise and cognition in the study of developmentally disabled individuals was conducted by James M. Oliver in 1958. Oliver was interested in examining the effects, if any, of the interaction of a physical conditioning programme and a battery of mental tests in adolescents, who were below normal educationally (mentally retarded). Thirty-eight boys were matched on age (13–15 year olds), intelligence quotient (IQ) (range from 54 to 81), size and physical conditioning. The control group remained in their respective physical education programme, which consisted of two classes a week plus additional organized games. The experimental group underwent a 10 week programme of physical education lessons, individualized remedial exercises, strength activities and recreational activities for five days per week. Each day consisted of 170 min of physical training and activity. Along with the physical activities were two instructional classes: English and mathematics, primarily as a recess from physical activity and to observe the effect, if any, of physical activity on these two subjects. Changes in physical conditioning were measured by a battery of: (1) selected McCloy's stunt type test items (i.e. balance, flexibility); (2) a modification of the Johnson Test (rolling forward and backward, half-turn and full-turn jumping); (3) athletic achievement as measured by 50 yard dash time, ball throwing and standing broad jump distance; and (4) a selection of tasks from the Indiana Motor Fitness Tests (push-ups, pull-ups, squats and vertical jump). Mental characteristics were measured by a battery of mental tasks involving the: (1) Terman Merrill IQ test; (2) Goodenough drawing of a man; (3) Raven's matrices; (4) Porteus maze; and (5) Goddard's form board.

Following the intervention, both groups improved on nearly all the physical and mental tasks, with the only exception being the control group decreased in performance from baseline on the Goodenough mental age test. Comparisons between the control group and the exercise group revealed the exercise group to have significantly greater improvements on all physical tests except for McCloy's stunt type test. The experimental group also saw significant improvements on three of the five mental tasks: the Terman Merrill IQ, the Goodenough mental age and the Porteus maze tasks. On the Terman Merrill IQ test, 18 of 19 students improved, with eight students achieving gains of five IQ points or more. What Oliver (1958) found was an increase in both physical and cognitive abilities in educationally sub-normal boys following a highly invasive (five days a week with 170 min of activity per day) intervention programme. The physical and cognitive gains in the control group were not identified as being significantly different from baseline, however.

The second study to examine the impact of an exercise programme on cognition in developmentally disabled individuals was conducted by Leighton *et al.* (1966) as a secondary investigation from the impact of a progressive physical fitness programme in 10 mentally retarded young adults (mean age of 23.1 years). Progressive strength (weight lifting), endurance (run–walk sequences) and coordination (hand–eye) development programmes were used to elicit exercise for three days a week for nine weeks. Each exercise session lasted two hours with a rotational (circuit) format so that all three programmes were performed at each session. The last 20 min of each session also included a low intensity group game, primarily intended for socialization. As mentioned previously, the primary investigation was to observe the effects of the progressive exercise programme; however, the researchers saw the opportunity to test for additional psychological and sociological outcomes. The authors tested for cognitive abilities using both the Peabody Picture Vocabulary Test (PPVT) and the Wechsler Adult Intelligence Scale (WAIS), however only the PPVT was administered pre-and post-intervention. In addition, only eight participants completed cognitive testing. Five of the participants scored higher on the PPVT following the exercise intervention. Statistical analyses on whether or not these increases were significant were not reported, yet it would appear not. The largest gain in IQ scores was four points (two participants), one participant increased three points and the remaining two participants improved two points on the PPVT. Yet one participant decreased ten points, resulting in an overall net loss of two points on IQ for the eight subjects pre- to post-exercise.

In 1966, Corder investigated the impact that a 20 day physical education programme had on the intellectual development of eight mentally retarded (50–80 IQ) adolescents (12–17 year-olds). These participants were matched, based on age and IQ, to a normal control group and a second control group who received similar amounts of attention but no instruction or participation in the physical education programme. The Wechsler Intelligence Scale for Children (WISC) was given to each participant pre- and post-intervention to test for any cognitive changes. Across five weeks, the exercise group participated in a total of 20 (four days a week), one hour physical education classes. Corder stated that a typical class involved activities such as jumping jacks, push-ups, sit-ups, 25 yard dashes, 400 yard run, broad jump, triple jump, and neck, finger and arm exercises. The pure control group remained in the normal school schedule of attending classes. The eight participants in the physical education intervention demonstrated significant improvements in IQ over the pure control group on the full scale and the verbal scale of the WISC, seven and eight IQ points, respectively. The experimental group also demonstrated a four point increase over the control group on the performance scale of the WISC, but this difference was found to be nonsignificant. However, when the experimental group was compared to the group receiving attention, no significant differences in IQ occurred.

Following the findings of Corder (1966) another hiatus, this time of 10 years, occurred before another study was published investigating the interplay of exercise and cognition in the developmentally disabled. Rarick, Dobbins and Broadhead (1976) published a book involving two studies. The second study is of particular interest.

Two hundred and seventy five mentally retarded (IQ of 50–70) and 206 minimally brain injured children, aged 10–13 years, were investigated on motor and strength performance, and intellectual development among several factors. Motor performance was measured by the modified Physical Fitness Test Battery of the American Association for Health, Physical Education and Recreation (1968), which involved sit-ups, flexed arm hang, 10 yard shuttle run, standing broad jump, 50 yard dash, softball throw and the 300 yard run. Strength performance was measured by grip strength, and the pull and thrust. Intellectual development was measured by the Bender Motor Gestält Test and the Peabody Picture Vocabulary Test. In addition to their motor, strength and intellectual performance, the participants were divided into four training conditions: (1) individualized physical education; (2) group-orientated physical education; (3) art programme; and (4) normal classroom instruction. The training interventions received planned instructions from the researchers and involved a 30 min daily programme for 20 weeks. Some of the planned activities in the physical education classes included walking, running, rolling, rocking and ball skills. Activities in the art programme included painting, pasting, cutting and construction. The normal classroom programme received no planned activities.

Results from the study indicated that children who participated in any of the three specialized training programmes improved significantly more in cognitive functioning than those taking part in normal classroom activities. However, participating in either physical education programme (individualized or group-orientated) was not significantly different to participating in the art programme. In addition, the minimally brain-injured children demonstrated larger improvements than the mentally retarded children. The authors concluded by suggesting that these improvements in IQ were due to taking part in a special programme, thus supporting the earlier findings of Corder (1966).

These early studies continued to focus on the impact of a physical education programme as a means for exercise and physical activity on improving cognition in developmentally disabled children. It was not until the mid-1980s that researchers began looking at the effects of exercise outside of the school setting and with adult populations with mental retardation. In 1984, Tomporowski and Ellis published their findings from their first experiment. Sixty-one moderate to profound mentally retarded adults (mean age of 29 years) were randomly selected for either a physical fitness group, an attention control group or a pure control group. In the physical fitness group, participants performed individually prescribed exercise plans (based on the results from a graded exercise test) for three hours, five days per week, for 28 weeks. The fitness sessions involved, but were not limited too, flexibility and callisthenic exercises, walking and running on a treadmill, stationary biking, swimming and weight lifting. The attention control group participated in an educational programme which encouraged academic and skill acquisition. Each lesson was individualized and occurred for similar times as the physical fitness group. The pure control group performed normal daily routines and treatments. Pre- and post-test cognitive changes were measured using the Stanford–Binet Intelligence Scale or, for those with verbal communication difficulties, the Leiter

International Performance Scale. In addition, pre- and post-test heart rates during the Physical Work Capacity test were measured. Despite substantially positive improvements in physical fitness of the exercising group, no significant changes occurred in intelligence scores.

The failure to observe any change in cognitive performance led Tomporowski and Ellis (1984) to replicate this study but with a more intensive physical fitness programme. The authors speculated that a change was not observed because any form of exercise programme would initiate improvements in physical fitness in mentally retarded adults because of their initially low levels of fitness and that the levels of physical fitness may be too low for an effect on cognition. Therefore, Tomporowski and Ellis (1985) proposed that a highly aerobic exercise programme might elicit changes in cognitive performance. Nineteen mentally retarded adults underwent an eight week circuit training programme consisting of treadmill walking and running, stationary cycling, rowing and isokinetic weight training for five days per week for three hours each day. Included each day was a 20 min walk/jog. This circuit training was intended to prepare the individuals for a physically challenging aerobic training programme. Intensity levels increased for each individual participant as needed. Following the circuit training the participants took part in a 20 week, aerobic exercise programme of circuit training, running and dance-aerobic programmes, with an emphasis on improving health-related fitness. Again, intensity increased from individual-to-individual as needed. These 19 individuals were sex, IQ and age matched to 19 pure controls. Pre- and post-test cognitive changes were again measured using the Stanford–Binet test. Tomporowski and Ellis (1985) found similar results as in their earlier study: exercise participants improved in physical fitness but not in their cognitive functioning, despite a more demanding exercise programme.

Tomporowski and Ellis (1985) study continued to support the evidence from previous studies whereby exercise does not provide any benefit (or detriment) to cognitive processes in those with developmental disabilities. The question of interest again lay dormant for several years. The next study to attempt to find any cognitive changes associated with chronic exercise in this population occurred in 1997 and found contradictory results. Lindsay *et al.* (1997) examined cognition not as an aspect of IQ but as levels of concentration. Eight profound learning disabled individuals (six women and two men, mean age of 39 years) underwent four therapy treatments with each session lasting 20 min and each treatment lasting for 20 sessions. The four therapies involved: (1) relaxation therapy; (2) hand massage and aromatherapy; (3) active therapy (jumping in a bouncy castle); and (4) snoezelen (multi-sensory stimulation therapy). Concentration was measured by being actively engaged with sorting tasks, geometric jigsaws and formboards. Lindsay *et al.* (1997) found that the active therapy resulted in no change in concentration, while snoezelen and relaxation therapies significantly improved concentration. While these authors lacked a control group to further support their findings, they found similar results to Tomporowski and Ellis (1984, 1985) and other earlier researchers on the effects of exercise on cognition in developmentally disabled individuals.

Summary of research findings

Table 14.1 summarizes the studies, and their findings, which have examined this issue thus far. The initial examination of the impact of exercise on cognitive performance in developmentally disabled individuals showed promise. Oliver (1958) observed improvements on three of five cognitive tests after the implementation of a fairly intensive intervention. Unfortunately, Oliver neglected to incorporate an attention control group and, therefore, attributed the gains in cognitive performance to the physical activity intervention and not to other factors or circumstances, such as the Hawthorne effect. Corder (1966) observed similar improvements in cognition, as measured by IQ, as Oliver (1958) when comparing the physical activity intervention group to a pure control group. However, Corder (1966) also implemented an attention control group, whereby a group of developmentally disabled adolescents received an equal amount of attention as those adolescents participating in the physical education programme. The addition of the attention control group was imperative in determining if participation in exercise or physical activity was the cause of cognitive improvements or if simply the extra time and attention given to the experimental group improved cognitive testing performance. What Corder observed was striking, the children in the physical education classes performed only slightly (and therefore nonsignificantly) better than the children in the attention control group. The idea that improvements in cognitive performance were solely due to exercise, as Oliver suggested, was not entirely accurate.

The findings of Corder (1966) were validated by Rarick, Dobbins and Broadhead (1976), who found significant improvements in cognitive performance for all adolescents in an intervention programme Rarick *et al.* found supportive evidence for Corder's assumption that a Hawthorne effect was present by demonstrating that the improvements in cognitive functioning were not significantly different across the three intervention programmes: individualized physical education, group physical education or art education classes.

One glaring methodological problem these early studies had in common was their interpretation, or use, of a physical education class as a means for eliciting physical activity and exercise. All four studies had attempted to investigate the impact exercise had on cognition, but had not properly controlled for the exercise interventions in a way to firmly link exercise and cognition. The dynamics of a physical education class are very different to purely exercising. A physical education class requires time for instruction, modeling and physical guidance for proper body movements, and encourages an atmosphere of learning and cognitive engagement. Usually, an emphasis is not placed on how hard one is exercising but rather on the quality of the movements, therefore individuals in the same class may be exercising at different levels of intensity. In addition, the cognitive engagement of the individual may be the cause of increased cognitive functioning rather than the exercise inducing any cognitive changes. To fully understand the dynamic interplay of exercise and cognitive process in the developmentally disabled, research had to be conducted that controlled for the level of exercise at which participants were performing.

Table 14.1 Summary of studies investigating the effect of chronic exercise on cognition in the developmentally disabled.

Study	Participants	Control Groups	Exercise	Cognitive Test(s)	Improved Cognition
Oliver (1958)	38 boys (13–15 yr old)	Pure Control Only ($n = 20$)	170 min/5 days/10 wk	1. Terman Merrill	Yes on 3 of 5 tests (Tests 1, 2 and 4)
	Developmental Disability: MR		P.E. classes	2. Goodenough drawing 3. Raven matrices 4. Porteus Maze 5. Goddard's Foam Board	
Leighton *et al.* (1966)	10 young adult males (mean age = 23 yrs)	Subjects were own control	120 min/3 days/9 wk	1. Peabody Picture Vocabulary Test	5 participants improved on PPVT (No statistical testing to confirm)
	Developmental Disability: MR		Strength, Endurance, Coordination	2. Wechsler Adult Intelligence Scale	
Corder (1966)	24 boys (12–17 yr old)	Pure Control ($n = 8$)	60 min/4 d/5 wk	1. Wechsler Intelligence Scale for Children	Yes
	Developmental Disability: MR	Attention Only Control ($n = 8$)	P. E. classes		No
Rarick (1976)	275 children (10–13 yr old)	Pure Control ($n = 66$)	30 min/5 d/20 wk	1. Peabody Picture Vocabulary Test	Yes
	Developmental Disability: MR	Attention Control (Art Class) ($n = 74$)	P. E. classes	2. Bender Motor Gestalt Test	No

(*continued*)

Table 14.1 (*Continued*)

Study	Participants	Control Groups	Exercise	Cognitive Test(s)	Improved Cognition
Tomporowski and Ellis (1984)	61 Adults (17–39 yr old)	Pure Control ($n = 22$)	180 min/5 d/28 wk	1. Stanford-Binet Intelligence Scale	No
	Developmental Disability: MR	Attention Only Control ($n = 19$)	Walking, Running, Swimming, Weight Lifting, Biking		No
Tomporowski and Ellis (1985)	40 Adults	Pure Control ($n = 17$)	180 min/5 d/28 wk		
	Developmental Disability: MR		(Includes 8 wk training programme) Walking, Running, Swimming, Weight Lifting, Biking	1. Stanford-Binet Intelligence Scale	No
Lindsay *et al.* (1997)	8 adults (23–62 yr old) Developmental Disability: Learning Disability	None	20 min/20 d Jumping	Engagement with: 1. Sorting Tasks 2. Geometric Jigsaw 3. Formboards	No

Tomporowski and Ellis (1984, 1985) saw this need and the need to examine adults with developmental disabilities and, therefore, attempted to control for participants' activity levels based on their physical work capacity. Initial levels of work capacity were achieved and used as guidelines for encouraging and increasing the intensity of exercise each subject performed. As subjects became accustomed to a level of activity, the researchers increased the intensity. Despite these additions to the research methodology, Tomporowski and Ellis found no changes in cognitive performance after the interventions. Surprising is the lack of improvement in either the physically active group or the attention control group over the pure control group, as found by Corder (1966) and Rarick, Dobbins and Broadhead (1976). The lack of this finding may possibly be due to the subject characteristic differentials between these studies. Tomporowski and Ellis used moderate to severe mentally retarded adults, who may be less influenced by the interactions with the researchers than the mild mentally retarded adolescents used in the studies of Corder and Rarick *et al.* Lindsay *et al.* (1997) found their activity session did not improve concentration, which supports the findings of Tomporowski and Ellis (1984, 1985), but using a rather different means of exercise intervention. The authors' attempt to use a bouncy castle as a means of physical activity and exercise is unique, however they lacked any control or standardization of the activity. Participants were 'encouraged to jump around and enjoy themselves' (Lindsay *et al.*, 1997). No attempt to maintain a pre-determined heart rate level was made, which could have provided a means of maintaining a specific level of intensity for each participant. The authors also fail to report the time in activity or the duration of inactivity. The lack of these two simple measures (heart rate and activity time) impedes knowing how much activity actually occurred and, therefore, if any true interaction may have transpired.

In general, the studies investigating the effect of exercise on cognition in the developmentally disabled individuals are not supportive of any empirical evidence for their association. A majority of the studies have not shown any significant positive or negative associations between exercise and cognition, rather the literature suggests that there is no interaction. There are, however, many issues to consider when examining these findings and attempting to make any generalizations about them.

14.3 Problems to address and future research considerations

First, there is a lack of control on exercise frequency, type, intensity and duration among the studies. Despite many of the early studies (pre-1980) focusing on physical education interventions, their methodologies were not identical. For instance, classes met from four to five days, for anywhere between five to twenty weeks and ranging from 30 to 170 min each day. Only the studies conducted by Tomporowski and Ellis (1984, 1985) had objective measures of physical fitness as part of their methodology. Unfortunately, these measures were only taken during the physical work capacity test

to provide a range of intensity of activity for the participants. None of the existing studies took into account monitoring the exercise/physical activity intensity level of the participants during exercise sessions. No observational data describing how many participants were engaged in neither physical activity nor the recording of effort were provided. It is plausible, especially in the physical education and bouncy castle interventions that subjects were not performing at intensity levels necessary to elicit an effect. In addition, without knowing if each participant is exerting similar effort, it is difficult to make accurate descriptions of the effect of exercise across the participants. Some participants may be exercising at very high levels, while others are at very low levels of intensity. It is impossible to say whether or not any participants reached a level of intensity that would elicit optimal performance as hypothesized by inverted-U theory (Yerkes and Dodson, 1908). In other words, the exercise may be too demanding and, therefore, too taxing for the brain to efficiently respond to the test, or the exercise understimulates and the participants perform worse. Developing studies where the intensity of exercise is known throughout the intervention is critical. Therefore, researchers can examine if the inverted-U theory is a plausible explanation for any changes by manipulating intensity levels across experiments and establishing a firm basis of exercise intervention. Within this scope, there are several other questions and considerations which need to be answered and addressed. These are presented briefly in the next section.

One possible avenue to explore is examining the effects of acute exercise on cognition and build from these findings. Maintaining similar frequencies, types, durations and intensities among participants and across studies would be easier. In two such studies, Croce and Horvat (1995) found that different levels of fitness were associated with different speeds of information processing following acute bouts (one session each) of 20 min and 30 min of exercise. More fit mentally retarded individuals had a facilitating effect of exercise, while the less fit individuals performed slower on arithmetic tests. These findings directly support the theory of activation and the inverted U-principle of activation levels. These studies incorporated pure control groups and attention only control groups, and controlled the intensity, duration and type of exercise for each individual. While Croce and Horvat did not attempt to examine the effect of acute exercise on cognition across several developmental disabilities, the need is there, and with such a setup it would be much easier to observe than with chronic exercise.

Second, of the seven studies reviewed, three of them had attention control groups. The other four failed to do so. It is highly feasible to attribute any changes in cognitive performance to exercise when inappropriate control groups are involved. The three studies, which utilized both normal control and attention control groups, showed that changes in cognitive performance may not be attributed to exercise at all but merely to the extra time spent with the participants. Future studies should continue the use of dual control groups to validate any findings.

Third, the studies have mainly focused on only one developmental disability: mental retardation. While future research should continue to examine this disability, others, such as autism and attention deficit disorder, should also be explored. Since

different developmental disabilities affect different parts of the brain in different ways, researchers may find no effect with one group and facilitation with another. These findings may lead to better understanding of brain processes and the validation or creation of new theoretical frameworks.

Fourth, different avenues of cognition need to be explored. The studies, thus far, have primarily (six of seven studies) examined intelligence scores as a means of cognitive changes following bouts of chronic exercise. Sibley and Etnier (2003) identified seven additional broad categories of cognitive assessments in normal children, while performing a meta-analysis investigating the relationship between cognition and exercise: (1) perceptual skills; (2) achievement; (3) verbal tests; (4) mathematics tests; (5) memory; (6) developmental level/academic readiness; and (7) other (i.e. creativity and concentration). Other cognitive evaluations, which show promise among normal children and the investigation of exercise and cognition, are event-related potentials (Hillman, Castelli and Buck, 2005). Croce, Horvat and Roswal (1996) have investigated the use of augmented feedback (knowledge of results) as a means of cognitive involvement and learning in adults with traumatic brain injuries, however their study did not involve exercise interventions. The need for studies involving these and other forms of cognitive assessments is apparent and opens the door further for the need of additional research in this area.

Several literature reviews have highlighted the miniscule amount known (or unknown) about the interaction of physical activity and exercise in developmentally disabled populations. Gabler-Halle, Halle and Chung (1993) discussed several recommendations for future research, highlighting the need for well-controlled studies with well-defined independent variables. In addition, the authors noted a need for future studies to identify the type, intensity, duration and frequency of physical activity that produces the greatest health benefits, both physiologically and psychologically, for developmentally disabled individuals. Additional reviews provided supportive evidence for the lack of investigations in the area of exercise and the developmentally disabled, and added further recommendations for future research. Rimmer, Braddock and Pitetti (1996) provided six explicit directions for future research: (1) provide estimates of physical activity on a condition-specific basis; (2) determine the barriers and determinants of physical activity among different sub-groups of persons with disabilities; (3) establish valid and reliable field-based testing instruments to evaluate the fitness levels of persons with disabilities; (4) identify the secondary complications associated with physical inactivity in persons with disabilities; (5) develop norms on the fitness levels of different subgroups of disabilities; and (6) design and test intervention strategies to promote physical activity for persons with disabilities. Similar directions for future research were echoed by Cooper *et al.* (1999) and Durstine *et al.* (2000) with additional recommendations including epidemiological studies, studies involving children, investigating the accessibility and safety of exercise programmes and, finally, identifying the effects of nutrition on health and the ability to exercise. As one can see, the lack of investigations among the developmentally disabled does not only include the areas of cognition but others as well.

14.4 Practical applications and conclusions

One of the most surprising findings in this literature is the lack of studies attempting to show the link between exercise and cognition in developmentally disabled populations. Reviews of the effects of exercise on cognition in normal functioning adults have found enough studies to suggest improvements following bouts of acute exercise (Tomporowski, 2003b), during and following exercise of both long and short durations at different levels of intensities (Tomporowski and Ellis, 1986), and even among older populations (Colcombe and Kramer, 2003). There is substantive evidence linking the positive effects of exercise on behaviour control and therapy for disabled children and adults, and improving their physical fitness (Dykens *et al.*, 1998; Gabler-Halle, Halle and Chung, 1993; Lanciono and O'Reilly, 1998). Why then, have so few studies (only seven could be found) examined the effects of chronic exercise on cognition among the developmentally disabled?

The potential answers to this question are numerous. One possible answer as to why so few studies have been conducted is the perception of the necessity for them. The major movements within developmental disability research since the 1970s have been focused on the concepts of functionality and independence. The major investigations into the benefits of exercise have been to examine how exercise can benefit the functionality and/or independence of the developmentally disabled. Primarily, the research has focused on the reduction of stereotypical behaviours to allow individuals the opportunity to focus and perform at an ideal level. Recently, more investigations have begun to examine the positive health benefits of exercise among the developmentally disabled. The calming effect of exercise may be an avenue towards independence for individuals, while they also receive substantial health benefits. As more research is conducted on the health benefits of exercise among the developmentally disabled, it may not be too surprising to see another push toward investigating the cognitive association.

An alternative answer may be the complexity of performing such research. As mentioned previously, there are numerous problems within the existing literature. One is getting a true representation of each disorder. For example, autism is highly associated (70% of all cases) with mental retardation (Fombonne, 2003). The co-morbidity which exists in developmentally disabled populations is not uncommon, in fact, it is very rare that a child expresses only one disability. In addition, the characteristics of each developmental disorder are broad and can cross over between disorders. One child with autism may not act or respond exactly like another child with autism and the same can be said for all of the disorders. These factors are major roadblocks for the generalizability of the research findings on, not only the impact of exercise on cognition, but any investigation in these populations.

The lack of investigations into the exercise–cognitive interactions has been highlighted throughout this chapter. Simply, more high quality studies are needed to merely understand the relationship which may (or may not, as most previous studies have suggested) occur. Identifying this relationship may provide clues and

more substantial evidence supporting the inverted-U theory, the activation theory or others. Future research may provide avenues for new discoveries into how the information processing system works and sends signals for motor function to be completed. These findings would not only help the developmentally disabled but lend new insights into how learning new skills among healthy individuals occurs.

15

Chronic exercise in brain diseases

Laura Eggermont and Erik Scherder

Given the growing segment of the aging population, interest in lifestyle factors and interventions that may stimulate cognitive function in aging and may reduce the risk of age-related neurodegenerative disorders, such as Alzheimer's disease, is increasing. The claim that physical activity enhances brain function, that is cognitive function, and is therefore associated with a reduced risk of neurodegenerative disease is supported by different kinds of research, including observational studies, animal experimental studies and human intervention studies (Kramer and Erickson, 2007). Several epidemiological studies show a positive relationship between the level of physical activity and cognitive functioning (Fratiglioni *et al.*, 2004; Laurin *et al.*, 2001; Rovio *et al.*, 2005; Van Gelder *et al.*, 2004). In one prospective cohort study, in which participants were assessed at baseline and after five years, it was observed that physical activity of a high intensity was associated with a reduced risk of cognitive impairment, particularly in women (Laurin *et al.*, 2001). A comparable association has been reported in men. Over a 10 year time interval, longer periods of physical activity and increased intensity of the activity were associated with less decline in cognitive functioning (Van Gelder *et al.*, 2004). Physical activity does not necessarily have to be vigorous to be associated with cognition (Yaffe *et al.*, 2001). In community-dwelling older women, it was shown that those who walked most blocks a week revealed less cognitive decline (Yaffe *et al.*, 2001).

The observational nature of these epidemiological studies, however, cannot establish causation (Fratiglioni *et al.*, 2004). There have been an increasing number of intervention studies in which older people participated in a physical activity programme and cognitive measures were assessed before and after the intervention. Results of these studies have been mixed, however most studies revealed positive effects (Kramer and Erickson, 2007). A meta-analysis showed that in older people, executive functions (EF), like planning and organizing, benefited most from the physical activity intervention (Colcombe and Kramer, 2003). Only a few studies investigated the effects of the physical activity intervention on human brain

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structure. Colcombe *et al.* (2006) performed a study in which older persons participated in either an aerobic activity programme or an anaerobic activity programme (stretching and toning exercises) for six months. The aerobic activity group showed increased grey matter volume in the frontal and temporal cortices, as well as an increase in the volume of anterior white matter (Colcombe *et al.*, 2006). Compared with the relatively small number of studies examining this issue in humans, there is substantially more evidence stemming from animal experimental studies. These studies report positive effects of exercise on brain function through neurogenesis, synaptogenesis and angiogenesis (for a review see Churchill *et al.*, 2002).

In view of the beneficial effect of physical activity on brain function, that is cognitive function, there is growing interest in the possibility of physical activity being able to postpone or reverse the consequences of neurodegenerative brain diseases (Kramer and Erickson, 2007). Neurodegenerative diseases encompass a wide spectrum of clinically and pathologically heterogeneous neurological disorders (Przedborski, Vila and Jackson-Lewis, 2003). In the literature, particular interest has been given to only some neurodegenerative diseases among which Parkinson's disease (PD), Alzheimer's disease (AD), Huntington's disease (HD) and amyotrophic lateral sclerosis (ALS) (Przedborski, Vila and Jackson-Lewis, 2003) are the most prominent. Studies with respect to the relationship between physical activity and cognition in neurodegenerative disease, however, have focused on dementia (mainly AD) and PD.

In this chapter, we will first describe both observational studies and physical activity intervention studies on cognition in patients with neurodegenerative disease, that is PD and dementia. Next, focus will be on cardiovascular disease since the presence of cardiovascular disease in dementia is often reported and its presence may affect the response to physical activity interventions. Within the scope of vascular disease, the role of nitric oxide (NO), a potent vasodilator, will also be discussed. In neurodegenerative disease, NO metabolism is disrupted, which may influence the response to physical activity. Therefore, the relationship between cardiovascular disease, NO and physical activity in neurodegenerative disease will be discussed. Finally, some recommendations concerning physical activity interventions in older people with neurodegenerative disease will be given.

15.1 Observational studies of physical activity

Epidemiological studies concerning the relationship between physical activity and the occurrence of PD show inconsistent results. In one study, physical activity appeared to be negatively associated with early onset PD, particularly in the presence of head trauma (Tsai *et al.*, 2002). A retrospective study revealed that regular exercise during teenage years was associated with a lower risk of PD, but this association did not turn out to be significant (Sasco *et al.*, 1992). In this study, the relationship between physical activity and PD seemed to be dependent on the level of exercise

participation. More specifically, engagement in a moderate amount of sports in adulthood was significantly associated with a reduced risk for PD, whereas participation in heavy sports was not (Sasco *et al.*, 1992). Another study that retrospectively determined level of physical activity during lifetime did not reveal differences between PD patients and healthy controls before the first symptoms of PD appeared (Fertl, Doppelbauer and Auff, 1993). Not surprisingly, after disease onset a marked decrease in engagement of physical activity was noticed (Fertl, Doppelbauer and Auff, 1993). In all of these studies, physical activity was determined retrospectively and all had relatively small sample sizes. A prospective cohort study showed that higher levels of physical activity before PD symptom onset were negatively associated with the risk for PD in men, but not in women (Chen *et al.*, 2005). This finding may be interpreted in two different ways: either higher levels of participation in physical activity may reduce the risk of PD in men or men predisposed to PD may have avoided strenuous exercise in the past (Chen *et al.*, 2005). Another recent prospective cohort study also did not find convincing evidence to support the hypothesis that engagement in physical activity (walking, stair climbing and sports activities) reduces the risk of PD (Logroscino *et al.*, 2006). Taken together, results concerning the relation between physical activity and risk of PD remain elusive.

Several studies have described the association between physical activity and the risk of AD. Prospective studies revealed a reduced risk of AD in individuals showing the highest level of physical activity (Abbott *et al.*, 2004; Larson *et al.*, 2006; Rovio *et al.*, 2005). One prospective study with a follow-up period of 21 years showed that the people engaging in physical activity at least twice a week during midlife had a lower risk of developing AD (Rovio *et al.*, 2005). With respect to the question, what aspect of physical activity is particularly associated with a delay in AD onset, it was shown that the number of different activities may be even more important than frequency or duration of the activity (Podewils *et al.*, 2005). Although the majority of epidemiological studies show a negative relationship between levels of physical activity and risk of AD, not all studies report such a relationship (Verghese *et al.*, 2003).

Most observational studies examining the relationship between level of physical activity and risk for dementia have focused on AD. Some studies also included other sub-types of dementia such as vascular dementia (VaD) (Lindsay *et al.*, 2004; Podewils *et al.*, 2005). Although the most important risk factors for VaD are cardiovascular risk factors (Román, 2005), and the benefits of physical activity on the cardiovascular condition are well known (Casillas *et al.*, 2007), studies investigating the association between physical activity and VaD reveal inconsistent results. In some studies, physical activity is associated with a reduced risk of VaD (Lindsay and Anderson, 2004; Podewils *et al.*, 2005), whereas this relationship has also been less apparent (Abbott *et al.*, 2004) or even absent (Verghese *et al.*, 2003). All in all, the majority of epidemiological studies report an association between level of physical activity and a decreased risk of dementia (e.g. AD), but some studies do not (Verghese *et al.*, 2003; Wang *et al.*, 2002). In one of these studies, however, the variables describing the level of physical activity were restricted to swimming, walking and

gymnastics. The authors state that only some people pursued these activities, rendering the power of the analysis to detect an association limited (Wang *et al.*, 2002). In another study (Verghese *et al.*, 2003), a positive association between a calculated 'physical activity score' for all types of activity and cognition was not found. However, a relationship between dancing and cognition was shown. Other physical activities, such as playing tennis or golf, could not be included in the 'physical activity score' since too few people engaged in those activities. Therefore, of the remaining activities, the dancing activity may have been one of the highest intensity, and the level of intensity appears to be associated with cognition (Scherder *et al.*, 2007b). As mentioned earlier, epidemiological studies do not provide information on the causality of the association, therefore in the next section, intervention studies will be discussed (for detailed information on the clinical intervention studies, see Table 15.1).

15.2 Physical activity intervention studies

Physical activity, cognition and Parkinson's disease

Animal experimental studies did reveal positive effects of physical activity on symptoms of PD. In animal models of PD, treadmill running induced a reduction in dopamine depletion in the striatum compared with control animals (Poulton and Muir, 2005) and resulted in the attenuation of behavioural and motor deficits (Tillerson *et al.*, 2003). In a PD rat model, forced exercise resulted in an increase in glial-derived neurotrophic factor (GDNF) which protects dopaminergic neurons (Cohen *et al.*, 2003). Additionally, wheel running activates the dopaminergic system and leads to enhanced levels of dopamine in the striatum (Hattori *et al.*, 1996).

Results from intervention studies in humans on the effects of physical activity on cognition are inconclusive. One exercise intervention study in PD patients combined physical therapy with motor imagery practice (Tamir, Dickstein and Huberman, 2007). Twenty-one PD patients completed a physical therapy programme of one hour, twice a week, over 12 weeks. Physical activities included callisthenics, practice of specific motor function, for example transfer skills, and relaxation exercises. The experimental group also performed motor imagery practice before and after the execution of the movements. Although the experimental group showed higher mean scores after the treatment on the cognitive measures, neither group showed a significant improvement in cognition. Another study offered an intensive twice a week exercise programme to PD patients for 14 weeks (Reuter *et al.*, 1999). One session took an hour and was performed once a week in the water, while the other session took place in a gymnasium. Participants were assessed at baseline, after 7, 14 and 20 weeks. Cognition, measured by a sub-scale of the Unified Parkinson's Disease Rating Scale (UPDRS) (Fahn and Elton, 1987) and a measure for global cognitive functioning, the Mini-Mental State Examination (MMSE) (Folstein, Folstein and McHugh, 1975), did not show significant changes during the entire

Table 15.1 Clinical intervention studies. Characteristics of studies examining the effects of physical activity on cognition in patients with neurodegenerative brain disease.

Study	Sample [men/women]	*N*	Age	Design	Type of Intervention	Dependent Variables	Results
Studies in PD patients							
Baatile *et al.*, 2000	Veterans with PD Severity of disability stage 2 or 3 according to the Hoehn and Yahr scale (1967)	6	$M = 72.7$	Single group; repeated measures	Pole striding training, three times a week for 37 ± 3 min for 8 wks	Standardized interviews concerning the severity of PD and quality of life.	4 out of 6 participants showed an improvement on the interviews, also on the cognitive dimension
	[6/0]		SD = 3.7				
Reuter *et al.*, 1999	Patients with idiopathic PD (UK-PDSBB criteria; Hughes *et al.*, 1992). Severity of disability ranging from 2 to 4 according to Hoehn and Yahr (1967)	16	$M = 65.4$	Single group; repeated measures	Twice a week training programme for 1 hr over 14 wks. Once a week water exercises and once a week exercises in a gymnasium including gait exercises and strength training	Rating scales for PD-specific motor disability, sport-specific disability MMSE, mood and sickness impact profile.	No significant change in cognition was found. Motor disability, mood and subjective well-being improved
	[9/7]		SD = 5.9				

(*continued*)

Table 15.1 (*Continued*)

Study	Sample [men/women]	*N*	Age	Design	Type of Intervention	Dependent Variables	Results
Tamir, Dickstein and Huberman, 2007	Community-dwelling patients with idiopathic PD. Severity of diasability between stages 1.5–3 according to Hoehn and Yahr (1967)	21	$M = 67.4$	Exp group/control group; repeated measures randomized procedure	Experimental group: combination of imagery and physical practice	Performance of movement sequence, balance functions, neurological and functional deficits, cognitive ability. Test administration was blinded	The experimental group showed higher gains in mental and motor tasks, but these gains were not significant
	[15/8]		SD = 9		Control group: only physical practice Physical practice in both groups included callisthenics, training of motor function, relaxation exercises. Sessions took 1 hr and were held twice a wk for 12 wks		
Studies in AD patients							
Arkin, 2001	Community-dwelling AD patients and nursing-home residents with AD	11	$M = 79$	Single group; repeated measures	Twice weekly physical fitness training of increasing duration for a mean of 30 min for 2 × 10 wks,	Neuropsychological tests	Performance on several cognitive tasks was maintained. Fitness and mood gains were obtained

	(NINCDS-ADRDA) MMSE: M = 23 (15–29) [3/8]		(59–86)			Mood questionnaires	
Arkin, 2003	Community dwelling AD patients (NINCDS-ADRDA)	24	M = 78.8	Single group; repeated measures	As for Arkin 2001, plus 10 recreational sessions	Neuropsychological tests (no details provided)	Cognitive decline was slowed and mood improved. Not further specified
	MMSE: 15–29 [8/16]		(SD = 8)			Mood questionnaires	
Cott *et al.*, 2002	Nursing-home residents with a medical diagnosis of AD	74	M = 82	Exp group/2 control groups; repeated measures Randomized procedure	Exp group: walking and talking in pairs for 30 min, 5 d a wk for 16 wks	Communication measures (administration was blinded)	No change in communication
	30 intervention		SD = 8		Social visit control group: conversation while sitting in pairs, in the same frequency	Ambulation, functional status (mental disorganization or confusion, physical disability, socially irritating behaviour and disengagement) (administration was not blinded)	No change in ambulation
	25 social visit control				Control group: no study-provided intervention		No change in functional status

(*continued*)

Table 15.1 (*Continued*)

Study	Sample [men/women]	*N*	Age	Design	Type of Intervention	Dependent Variables	Results
	19 control MMSE: Exp group I: M = 6.2; Exp group II: M = 5.4 Control group: M = 6.3 [35/39]						
Friedman and Tappen, 1991	Nursing home residents with probable AD (NINCDS-ADRDA criteria and MMSE scores < 19) MMSE: Exp group: M = 6.5; Control group: M = 6.4 [17/13]	30	M = 72.8 (60–87)	Exp group/control group; repeated measures randomized procedure	Exp group: 30 min walk 3 times a week for 10 wks Control group: conversation only in the same frequency	Communication scales. Administration was not blinded but inter-rater reliability was checked	Improvement in communication in the experimental group. Conversation only did not result in a significant improvement
Lindenmuth and Moose, 1990	People with AD	43	M = 82.8	Exp group/control group; repeated measures	Exp group: somatic and isotonic-relaxation exercises for 8 wks	Cognitive Abilities Screening Test. Unclear whether test administration was blinded	Experimental group showed significant improvement

	[27/16]		(65–98)	No randomized procedure	Control group: no intervention		
Palleschi *et al.*, 1996	Males diagnosed with possible AD (NINCDS-ADRDA criteria, MMSE: 18–21	15	M = 74.0	Single group; repeated measures	Exercise on an exercise cycle (heart rate at +/− 70% of max pulse rate)	Test of attentional matrix, verbal span tests, MMSE	Significant improvement on all tasks
	[0/15]		SD = 1.5		20 min exercise 3 d a wk, for 3 mo		
Rolland *et al.*, 2000	People with probable AD (NINCDS-ADRDA criteria)	23	M = 78	Single group; repeated measures	Endurance exercise: walking, exercise cycle for 5–12 wks (M = 7) for 35 min (10–80 min)	Scales for (Instrumental) Activities of Daily Living; MMSE; behavioural questionnaire; nutritional assessment; test for balance	Improved nutritional status, improved cognitive function, improvement in behavioural problems
	[13/10]		(71–92)				
Studies in 'dementia'							
Baum *et al.*, 2003	Frail long-term care-facility residents	20	M = 88	Exp group/control group; repeated measures	Exp group: exercise programme containing seated strength and range of motion exercises	MMSE and physical function measures. Test administration was blinded	Increased MMSE score and physical function improved
	MMSE: Exp group M = 21; control group M = 22		(75–99)	Randomized procedure	Control group: recreational therapy		
	(10–29)				1-hr sessions, 3 times a wk, during 6 mo		

(*continued*)

Table 15.1 (*Continued*)

Study	Sample [men/ women]	*N*	Age	Design	Type of Intervention	Dependent Variables	Results
De Carvalho Bastone and Filho, 2004	Nursing home residents	37	Exp group M = 76.8	Exp group/Control group; repeated measures	Exp group: exercise programme including mobility exercises, strengthening exercises and walking	MMSE, mood questionnaire, functional performance tests. Unclear whether test administration was blinded	Maintenance of MMSE score compared with the control group. Improvement of mood and physical performance
	MMSE: Exp group		Control group	No randomized procedure	1 hr, once a wk, for 6 months		
	M = 19.2; Control group		M = 80.3		Control group: no study-provided intervention		
	M = 20.9		(60–99)				
Hopman-Rock *et al.*, 1999	Nursing home residents	92	Exp group M = 83.8 (SD = 5.8)	Exp group/control group; repeated measures randomized procedure	Exp group: twice weekly 'psychomotor activation (PAP)' for 45 min over 6 months. PAP consists of sporting activities, games and hobby activities	Cognitive screenings test ($n = 61$, test administration was blinded) and behavioural questionnaires (unclear whether administration was blinded	
	Stabilized cognitive function in the PAP group and increased positive group behaviour in those with mild problems						

	45 intervention 47 control Cognitive screening test-20: Exp group: M = 5.1; Control group: M = 6.1		Control group M = 84.2 (SD = 5.6)		Control group: no study-provided intervention		
McMurdo and Rennie, 1994	Nursing-home residents MMSE: Exp group M = 15.7; Control group M = 15.2	55	M = 83 (67–98)	Exp group/control group; repeated measures Randomized procedure	Exp group: seated exercises to music Control group: reminiscence therapy All sessions for 45 min, twice weekly, for 6 months	MMSE, reaction time and physical function measures. Unclear whether test administration was blinded	No improved performance on the MMSE. No improved reaction time. Improvement of physical function in both groups
Mulrow *et al.*, 1994	Nursing home residents	180	Exp group	Exp group/control group; repeated measures.	Exp group: three times a week exercise to music training, containing range-of-motion exercises, balance, transfer and endurance training for 30–45 min, for 4 months	MMSE, mood questionnaire, physical function measures, ADL scale. Test administration was blinded accept for ADL	Performance on the MMSE did not improve. No change in feelings of depression. No change in ADL. Small increase in physical function

(*continued*)

Table 15.1 (*Continued*)

Study	Sample [men/ women]	*N*	Age	Design	Type of Intervention	Dependent Variables	Results
	MMSE: M = 21		M = 79.7 (SD = 8.5) Control group M = 81.4 (SD = 8.5)	Randomized procedure	Control group: social visits with the same frequency		
Powell, 1974	Geriatric mental patients	30	M = 69.3 (59–89)	Two treatment groups/control group; repeated measures Randomized procedure	Exercise intervention I: 1 hr a day, 5 d a wk exercise therapy, involving walking and callisthenics, for 12 wks, Social therapy intervention: Arts and crafts work, music therapy and games playing in the same frequency Control group: No study-provided intervention	3 cognitive tests, 2 behavioural questionnaires Unclear whether test administration was blinded	Cognition improved, behavioural problems increased

ADL = activities of daily living; Exp = experimental; hr = hour; M = mean; min = minutes; MMSE = Mini Mental State Examination; NINCDS = National Institute of Neurological and Communicative Disorders and Stroke; SD = standard deviation; wk = week.

Van de Winckel *et al.*, 2004	Female patients with dementia living in a psychiatric hospital	25	Exp group M = 81.33 (SD = 4.2)	Exp group/Control group; repeated measures	Exp group: Daily 30 min seated exercise programme, containing upper and lower body strengthening, balance, trunk movements and flexibility straining, supported by music for 3 months	MMSE, dementia screenings test including measures of memory and word fluency (administration was not blinded), behavioural questionnaire (administration was blinded)	Improved score on the MMSE and a verbal fluency task. No change in behaviour
	MMSE: Exp group M = 12.9; Control group M = 10.8		Control group M = 81.9 (SD = 4.2)	Randomized procedure	Control: daily conversation in the same frequency		

AD = Alzheimer's disease; ADRDA = Alzheimer's Disease and Related Disorders Association; hr = hour; M = mean; min = minutes; MMSE = Mini Mental State Examination; NINCDS = National Institute of Neurological and Communicative Disorders and Stroke; PD = Parkinson's disease; SD = standard deviation; UK-PDSBB United Kingdom Parkinson's Disease Society Brain Bank; wk = week; Exp = experimental; ADL = activities of daily living

study period (Reuter *et al.*, 1999). A limitation of the study was the lack of a control group. In a small study, six male PD patients engaged in a training programme for eight weeks (Baatile *et al.*, 2000). The programme focused on a polestriding activity, that is a walking activity with the use of poles in a similar way to cross country skiing. Training took place three times a week for one hour. After the intervention programme, four out of the six patients showed a higher score on a self-administered survey measuring cognition. In view of the limited sample size and lack of a control group, results should be interpreted with caution.

All in all, there is a paucity in physical activity intervention studies in PD patients that focus on cognition and the assessment of cognitive functions is limited. The few studies that did investigate this issue do not report significant positive findings or are characterized by methodological shortcomings.

15.3 Physical activity, cognition and different types of dementia

The four most common sub-types of dementia are AD, VaD, dementia with Lewy bodies (DLB) and frontotemporal dementia (FTD) (Bastos Leite, Scheltens and Barkhof, 2004). Effects of exercise on cognition in these four major sub-types of dementia are discussed below. Unfortunately, many physical activity intervention studies did not specify the sub-type of dementia of the participants, but will be reviewed here as well.

Alzheimer's disease

In an AD mouse model, wheel running activity initiated up-regulation of hippocampal brain-derived neurotrophic factor (BDNF) and hippocampal neurogenesis (Wolf *et al.*, 2006). One study, using a mouse model of AD, showed that pathology characteristic of AD, amyloid plaques, were significantly reduced after voluntary wheel running for one month (Adlard *et al.*, 2005). These findings were confirmed in another study that examined AD mice living in either an enriched environment or in standard cages (Lazarov *et al.*, 2005). Mice that lived in the enriched environment and had access to running wheels showed a reduced amyloid burden (Lazarov *et al.*, 2005). In contrast, another study showed that the AD mice that lived in the enriched environment showed increased amyloid load (Jankowsky *et al.*, 2003). However, the enriched environment condition showed a lower number of running wheels, which limited the opportunity to run and may have led to competition and stress (Lazarov *et al.*, 2005).

There have been some intervention studies that examined the effects of a physical activity programme on AD patients. Some studies offered an intervention programme that offered a form of physical activity only ('exclusively physical activity'), whereas other studies offered a form of physical activity combined with another type of stimulation, for example music, rendering conclusions on what type of intervention was (most) beneficial impossible. Therefore, these studies will be described separately.

Exclusively physical activity

Only a few studies have implemented exercise programmes in studies that included AD patients. In one study, a group of 23 moderate to severe AD patients participated in a programme of endurance exercise that consisted of walking and riding an exercise cycle for a mean of seven weeks (5–12 weeks) (Rolland *et al.*, 2000). After the intervention, they showed significantly improved performance on a measure of global cognitive functioning, the MMSE. The time the patients participated in the daily activity programme varied considerably, from 10 to 80 min. Another study offered an exercise programme consisting of riding on an exercise cycle for more than 20 min a day, three days a week for three months to 15 males with possible AD. Following the intervention, they showed an improvement in their performance on three tests of attention and short-term memory and the MMSE (Palleschi *et al.*, 1996). It is noteworthy, however, that a control group was lacking in both of the aforementioned studies. Finally, one study reports positive effects on cognition after an eight week exercise programme that included somatic and relaxation exercises. The precise nature of the cognitive abilities was unfortunately not further specified (Lindenmuth and Moose, 1990). Also, the participants were allowed to choose whether they preferred to be in the experimental or control group. Moreover, participation in the exercise group was irregular and the control group did not take part in any alternative activity.

In sum, all three studies that included AD patients report an improvement in global cognitive functioning after participation in an exercise programme. Nevertheless, these results should be interpreted with caution, in view of the methodological flaws.

Physical activity combined with another type of intervention

In a pilot study, 11 patients with mild to moderate AD followed a twice-weekly physical fitness training programme, containing a variety of exercises, such as aerobic and weight resistance activities, for 10 weeks (Arkin, 2001). Seven out of the 11 participants also received specific memory and language stimulation exercises, for example playing word games. The study suggested that the exercise prevented a significant cognitive decline in the participants, regardless of whether the participants had received memory and language training. The small sample size and lack of a nonexercise control group are limitations of the study. In a longitudinal follow-up study, a comparable exercise programme, adding 10 recreational activity sessions, was followed by 24 patients with AD during a period of one to four years (Arkin, 2003). Results suggest the slowing of cognitive decline. Unfortunately, details concerning the cognitive benefits were not provided. Moreover, a control group was lacking. Two studies did offer randomized controlled trials and examined the effects of walking combined with talking on communication skills in AD patients. The results of the two studies were conflicting. Thirty moderate to severe AD patients were randomly allocated to two groups: the experimental group, which received a 30 min walking and conversation programme, and a control group that received a 30 min conversation-only programme (Friedman and Tappen, 1991). After the

10 week treatment period, communication improved only in the group that was offered walking combined with conversation. These results were not confirmed in another study, in which 90 AD patients were randomly assigned to three groups: a walking and conversation group, a conversation-only group and a nonintervention control group (Cott *et al.*, 2002). The interventions were applied for 30 min, five days a week for 16 weeks. Social communication skills and communication of basic needs were not found to be improved after the intervention period in the walking and conversation group compared with the other two groups. Notably, the participants demonstrated large differences in level of cognitive impairment at baseline, but most showed severe cognitive impairment. The participants may have been too severely cognitively impaired to benefit from the intervention (Cott *et al.*, 2002).

In sum, studies including AD patients that investigated the effects of a physical activity intervention in combination with another type of stimulation have shown inconsistent results. The inconsistency in findings may be attributed to differences in study design or the stage of dementia of the participants.

Vascular dementia, dementia with lewy bodies and frontotemporal dementia

As far as the authors know, studies examining the effects of physical activity on cognition have not been performed with respect to VaD, DLB and FTD.

Older persons with 'dementia'

Exclusively physical activity

Thirty psychogeriatric patients were allocated at random to a group that received exercise therapy, a group that received conventional social therapy or a nonintervention control group (Powell, 1974). Both interventions were offered five days per week and lasted an hour. After 12 weeks of treatment, only the exercise group showed improved performance on tasks that appeal to logical reasoning and memory. In a more recent study (De Carvalho Bastone and Filho, 2004), 40 people living in a nursing home were assigned to either an exercise group or a nonintervention control group. The exercise programme, which involved walking, mobility exercises and strength training was offered twice a week for one hour. After six months, performance on the MMSE was maintained in the exercise group, whereas the performance on the MMSE deteriorated significantly in the control group. Lack of a randomized procedure is a limitation of the study. In another study (Baum *et al.*, 2003), 20 frail, long-term care-home residents participated and were randomly assigned to two groups. One group received an exercise programme containing seated range of motion (ROM) exercises and strength training for one hour, three times per week and the other group received recreational therapy with the same frequency. After six months, performance on the MMSE improved significantly only in the group that attended the exercise programme. In contrast, in a study in which 189 frail, nursing-home residents participated (Mulrow *et al.*, 1994), performance on the MMSE was not

found to be improved after four months of physical therapy. In this study, the nursing home residents were randomly divided to either physical therapy sessions or friendly visits for three times a week. Physical therapy involved ROM exercises, resistance exercises, endurance activities and gait training.

In sum, the effects on cognition in studies offering exercise programmes in nursing-home residents have been inconsistent.

Physical activity combined with another type of intervention

Fifteen women with dementia participated in an exercise programme, which consisted of daily seated exercises supported by music (Van de Winckel *et al.*, 2004). The control group, which consisted of 10 patients, received conversation with the same frequency. Compared with the control group, the exercise group showed a significant improvement on the MMSE and a verbal fluency measure after three months. These beneficial effects were, however, not confirmed in another randomized controlled study that offered a comparable intervention. Sixty-five older nursing-home residents were randomly assigned to either a seated exercise to music intervention or a reminiscence intervention offered twice-weekly, for 45 min over 6 months. Neither group showed improved reaction time or improved MMSE score after the intervention period (McMurdo and Rennie, 1994). In a randomized controlled study, including people with dementia, the effects of a psychomotor activation programme (PAP) were investigated. This programme was offered twice a week and involved sporting activities, games and hobby activities in order to stimulate cognitive and psychosocial functioning. Sixty-one nursing-home residents with dementia completed either the PAP programme or attended no specific intervention but took part in their regular activities. Results indicated that the residents that participated in the PAP programme maintained their global cognitive functioning, whereas the control group deteriorated (Hopman-Rock *et al.*, 1999).

In sum, results of studies investigating the effects of a combination of physical activity with another type of stimulation with older people living in long-term care facilities show inconsistent results. It is noteworthy that in all the above-mentioned studies on residents of long-term care facilities, the residents generally appeared to be cognitively impaired, but whether *all* participants were cognitively impaired remains elusive.

Overall conclusion

Most studies concerning the effects of physical activity on cognition in neurodegenerative diseases have focused on patients with AD or 'dementia', and only a handful on patients with PD. Some studies are characterized by serious methodological flaws such as small sample sizes (Arkin, 2001; Baatile *et al.*, 2000), the lack of a control group (Arkin, 2003; Palleschi *et al.*, 1996; Reuter *et al.*, 1999; Rolland *et al.*, 2000), no randomized procedure (De Carvalho Bastone and Filho, 2004; Lindenmuth and Moose, 1990) and unblinded test assessment or no clarity to it (Friedman and

Tappen, 1991; McMurdo and Rennie, 1994; Powell, 1974). In addition, where physical activity has been combined with another type of activity, beneficial effects cannot be purely attributed to the exercise performed. Apart from these flaws, results of the studies have been inconsistent. A number of factors may be responsible for these inconsistent findings, for example the role of physical activity duration, intensity and frequency, and the cognitive functions examined in the studies (Kramer and Erickson, 2007). However, characteristics of the participants may also play an important role, especially age, gender, differences in the stage of the disease, brain areas and molecular factors most affected, and co-morbidity of diseases (Kramer and Erickson, 2007; Scherder *et al.*, 2007a). It will be important for future research to characterize the people that will benefit most and those that will benefit least from a physical activity intervention.

15.4 Role of vascular disease

One type of co-morbidity frequently present in older people with dementia is vascular disease, that is hypertension (Wolozin and Bednar, 2006). It is suggested in this chapter, that the presence of vascular disease may particularly moderate the effect of physical activity on cognition in some older people with neurodegenerative disease (Eggermont *et al.*, 2006; Scherder *et al.*, 2007a). This may sound somewhat counter-intuitive, since cardiac patients generally are advised to exercise (Casillas *et al.*, 2007). However, in the present chapter, we will describe how exercise may benefit cognition in neurodegenerative disease, but how vascular disease may disrupt cerebral autoregulation and hence the ability of physical activity to stimulate cerebral blood flow.

Vascular disease and cerebral hypoperfusion have been reported in different types of neurodegenerative disease. Hypoperfusion in PD has been reported in parieto-temporo-occipital cortex, dorsolateral prefrontal cortex, cingulate gyrus and insula (Hsu *et al.*, 2007). In addition, reductions in regional cerebral blood flow in the left temporo-parietal region discriminated PD patients with dementia from PD patients without (Derejko *et al.*, 2006). Vascular disease in PD may even show a synergistic effect on cognitive decline (Demirkiran *et al.*, 2001).

Vascular disease has also been reported in different sub-types of dementia. There is growing support for the notion that AD may have a vascular basis (De La Torre, 2002). Besides the similar risk factors for cardiovascular disease and AD, among which are hypertension, atherosclerosis and diabetes (De La Torre, 2002), evidence from AD mouse models and reports on severe reduction in cerebral blood flow (CBF) confirm the contribution of vascular factors to AD (Iadecola, 2004). In addition, abnormalities in the brain microvascular system are frequently reported in AD (Farkas and Luiten, 2001). Impairment in cognition can be the result of dysfunctioning of blood vessels through impaired nutrient transport to neurons and impairment in amyloid-β (Aβ) clearance from the brain (Iadecola, 2004). Indeed, the relationship between Aβ deposition and cerebrovascular disease may lead to a

vicious circle in AD pathology: while Aβ produces cerebrovascular dysregulation and an increase in the susceptibility of the brain to cerebral ischaemia, ischaemia in turn stimulates the amyloid precursor protein (App) and Aβ cleavage (Iadecola, 2004). Aβ-induced cerebrovascular dysfunction might also reduce blood flow sufficiently to produce ischaemic injury (Iadecola, 2004). Due to disturbance of cerebrovascular autoregulation, the sub-cortical white matter is highly susceptible to infarction, which may provide an explanation for the frequently observed white matter infarcts in AD (Barber *et al.*, 1999). Another important feature of AD is the formation of cerebral amyloid angiopathy (CAA) which constitutes a combination of pathology typical for AD (amyloid) and vascular pathology (angiopathy). CAA results from the deposition of protein, among which is the Aß-precursor protein, in the cerebral blood vessel walls (Castellani *et al.*, 2004). CAA can lead to ischaemia and haemorrhage, which aggravates the course of AD (Castellani *et al.*, 2004).

With respect to VaD, the common causal element is cerebrovascular disease. The main risk factors of VaD are advanced age, hypertension, diabetes, smoking, hyperhomocysteinaemia and hyperfibrinogenaemia, (Román *et al.*, 2002). The presence of hypertension particularly increases the risk of VaD (Posner *et al.*, 2002). Hypertension and other cardiovascular risk factors can lead to arteriosclerosis which, in turn, can cause cerebral infarction (Román *et al.*, 2002). Other conditions that can result in cerebral hypoperfusion are risk factors for VaD as well, among which obstructive sleep apnoea, congestive heart failure, cardiac arrhythmias and orthostatic hypotension are prominent (Román, 2005). Studies measuring reduction in cerebral perfusion in DLB patients reveal mainly frontal lobe hypoperfusion compared with AD patients (Defebvre *et al.*, 1999; Kasama *et al.*, 2005). In addition, besides hypoperfusion in the lateral parietal and temporal regions and the precuneus (Mito *et al.*, 2005; Shimizu *et al.*, 2005), marked hypoperfusion in the occipital regions has been reported in DLB (Ceravolo *et al.*, 2003; Hanyu *et al.*, 2006; Shimizu *et al.*, 2005). White matter abnormalities have been reported in the parietal, frontal and occipital regions (Bozzali *et al.*, 2005), however presence of white matter hyperintensities (WMH) did not differ between controls in another study (Burton *et al.*, 2006). Nonetheless, people with DLB frequently present with neurocardiovascular instability, such as orthostatic hypotension (Kenny, Kalaria and Ballard, 2002), which, in turn, has been associated with increased WMH (Ballard *et al.*, 2000).

Support for a vascular involvement in the pathogenesis of frontotemporal lobar degeneration (FTLD) comes from several studies revealing a marked cerebral hypoperfusion in the affected regions (frontal and temporal areas) (Diehl-Schmid *et al.*, 2007; Du *et al.*, 2006; Hodges, 2001). In frontal variant FTD (fvFTD), the exact location of hypoperfusion in frontal and temporal areas seems to be dependent on the behavioural features, such as inertia and disinhibition (Le Ber *et al.*, 2006). Further evidence for vascular involvement stems from another study, in which degenerating astrocytes in FTD were inversely correlated with cerebral perfusion (Martin *et al.*, 2001). Since astrocytes have been shown to degenerate in response to hypoxia and ischaemia, it is speculatively suggested that the reduced cerebral perfusion has a causal role in disease progression via ischaemic or hypoxic insult (Martin *et al.*, 2001). Finally, white

matter changes are already present in an early stage of both fvFTD and temporal variant FTD (tvFTD) (Borroni *et al.*, 2007).

In sum, in all types of dementia and in PD (especially in those with dementia), cerebrovascular disease and cerebral hypoperfusion have been reported. Since in the regulation of cerebral blood flow, NO, a potent vasodilator, plays a crucial role (Furchgott, 1996), NO regulation in neurodegenerative disease and exercise will be discussed.

Levels of nitric oxide in neurodegenerative disease

NO is derived from vascular endothelial nitric oxide synthase (eNOS) and plays a crucial role in the cerebral perfusion by influencing vascular tone, blood pressure and vascular homeostasis (Eggermont *et al.*, 2006; Huang *et al.*, 1995; Kubes and Granger, 1992). NO mediates cerebral autoregulation (White, Vallance and Markus, 2000) and protects endothelial cell function (Maxwell, 2002). NO is involved in the pathogenic processes in various neurodegenerative diseases (Zhang, Dawson and Dawson, 2006). How NO specifically contributes to these diseases remains elusive, however progress has been made on our understanding of the role of NO in PD and other neurodegenerative diseases (Boje, 2004). Both post-mortem studies on PD brains and studies with PD mouse models lend support to a role of NO in the pathogenic process (Zhang, Dawson and Dawson, 2006). Disruption of NO levels in AD is recognized to contribute to the pathogenesis in AD (Corzo *et al.*, 2007). It has been suggested that cerebral hypoperfusion in AD disturbs NO metabolism, which in turn causes vascular injury (Cooke and Dzau, 1997). More specifically, it is suggested that when the cerebral perfusion is reduced to a certain threshold, NO levels are up-regulated to maintain vascular homeostasis (De La Torre, 2002). In failing to do so, NO levels become even more disrupted which may damage the endothelial cells and impair glucose transport to the brain (Chen *et al.*, 1999). NO is also known to play a role in the pathogenesis of VaD (Corzo *et al.*, 2007). Levels of NO have been shown to be reduced (Corzo *et al.*, 2007). In contrast, it has also been reported that NO levels do not differ between VaD patients, AD patients and healthy controls (Folin *et al.*, 2005). A possible explanation for these conflicting results could be that NO levels differ between sub-types of dementia, that is Binswanger's disease and multiple small infarct type (Tohgi *et al.*, 1998), and depend on the stage of dementia (Tohgi *et al.*, 1998). Also patients with dementia with DLB show microvasculopathy and impaired NO release (Katsuse, Iseki and Kosaka, 2003; Togo, Katsuse and Iseki, 2004).

It can be concluded that vascular disease and nitric oxide appear to be involved in neurodegenerative disease.

Nitric oxide metabolism and physical activity

There is a relationship between NO, cerebral perfusion and physical activity, that is exercise. In animal experimental studies, NO release is increased by exercise,

especially in the hippocampus (Endres *et al.*, 2003). Enhanced NO leads to vasodilatation and consequently to increased cerebral perfusion, which may improve cerebrovascular function (Kubes and Granger, 1992). In addition, tissue-type plasminogen activator (t-PA), which is released by NO, (Schini-Kerth, 1999), is also elevated after physical activity (Smith *et al.*, 2003). t-PA is an enzyme that converts plasminogen – an active proenzyme (Lijnen and Collen, 1997) – into plasmin (Melchor, Pawlak and Strickland, 2003), which in turn reduces fibrin clots in the circulation. Therefore, t-PA plays a pivotal role in the prevention of thrombosis (Muldowney and Vaughan, 2002). An enhancement of t-PA levels by exercise may improve endothelial fibrinolytic function (Smith *et al.*, 2003).

In sum, cerebral hypoperfusion may be ameliorated by exercise by means of NO and t-PA enhancements.

15.5 Neurodegenerative disease, nitric oxide, vascular disease and physical activity

As described earlier, several types of neurodegenerative disease show disruptions in NO metabolism. NO levels may be even more affected in cases of cardiovascular disease, causing additional damage to the endothelium (Valgimigli *et al.*, 2003). It is suggested, in this chapter, that increased physical activity may not necessarily be beneficial under all circumstances. More specifically, attention should be paid to cases that show neurodegenerative disease in combination with cardiovascular disease. Notably, increased plasmin levels by enhanced t-PA release may also reduce the level of laminin (Chen and Strickland, 1997), a protein that decreases neurotoxicity in AD (Morgan and Inestrosa, 2001) and protects dopaminergic neurons in PD (Väänänen *et al.*, 2006). Particularly in the presence of ischaemic lesions, plasmin degrades laminin and can cause neuronal damage (Wang *et al.*, 1998). In other words, (high-intensity) physical activity may lead to laminin depletion and hence to neuronal damage. It is, therefore, of great importance to maintain the laminin concentration at physiologically normal levels. Moreover, in patients with a reduced cardiac output resulting from cardiac disease, the blood supply to the large muscle cells may preclude increased cerebral blood flow (Koike *et al.*, 2004). The positive effects of exercise on cerebral perfusion, therefore, appear to rely on the presence of cardiovascular risk factors and the patient's cardiac condition.

15.6 Final conclusion

In this chapter, we have summarized that all the major sub-types of dementia show cerebrovascular disease. In view of the aforementioned risk of, for example, ischaemic lesions, it is suggested that physical activity in older people with neurodegenerative disease should not be prescribed light-heartedly, but under conditions

involving careful medical screening and close monitoring. It is recommended in future research on the effects of physical activity in older people with neurodegenerative disease that one should control for co-morbid vascular disease and cardiovascular risk factors. These risk factors might attenuate or undo beneficial effects of exercise on cognition, or may even pose a risk for the patient in exercise. In conclusion, participation in exercise in addition to one's usual physical activities may not be beneficial in all cases of neurodegenerative disease. A take-home message with respect to exercise in neurodegenerative disease may thus be: 'more is not necessarily better'.

PART 4

DISCUSSION AND CONCLUSION

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16

Summary and direction for future research

Terry McMorris, Phillip D. Tomporowski, and Michel Audiffren

In this chapter, we reflect on information provided by the contributors to this book and comment on the current status of the study of exercise and cognitive function. We have divided our commentary into four sections. In the first section, we examine the emergence of theories that have driven recent empirical research. In the second, we evaluate the cohesiveness of the main research findings to date (or rather at the time of going to press). Third, we provide recommendations concerning future theory-based research. Lastly, we comment on the value of research findings for addressing real-world practical issues.

16.1 Summary: emerging theoretical approaches

Acute exercise

Early research into the effects of both acute and chronic exercise on cognitive function tended to be atheoretical and generally lacking in rigour. With regard to acute exercise, the first to apply a theoretical approach was the Australian physical educator Colin Davey (Davey, 1973). Davey based his rationale on the assumption that exercise is a stressor and will, therefore, affect cognitive performance in the same way as any other stressor, that is exercise would induce an inverted-U effect on cognitive function. Although research has provided very limited support for Davey's claims, physical education and sports science texts repeatedly state as fact that exercise has an inverted-U effect on cognition. Moreover, the early research designs were at times banal, with very limited attempt to control the exercise intensity or take into account individual differences in fitness levels.

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Although there were a few notable exceptions (e.g. Bard and Fleury, 1978; McGlynn *et al.*, 1977), the situation remained this way until Tomporowski and Ellis' (1986) seminal paper was published.

Tomporowski and Ellis (1986) highlighted several theories that might explain the exercise–cognition interaction. Following this review, several authors based their rationales on cognitive-energetic theories, for example those of Kahneman (1973) and Sanders (1983). Sanders proposed that there are three energetic mechanisms, which allocate processing resources, and an evaluation level that corresponds to an executive function, which manages processing resources. Thus, the energetic factors will be highly activated by exercise, while effort will be responsible for allocation of resources. Psychoneuroendocrinology rationales support the cognitive-energetic model in that exercise-induced increases in neurotransmitters are seen as playing a vital role in increased arousal. However, some authors, ourselves included, feel that this is an incomplete answer.

In Chapter 3, Dietrich proposes the theory of hypofrontality as an explanation for the exercise-cognition interaction. It is an interesting, but somewhat controversial theory. Dietrich's early papers (Dietrich, 2003; Dietrich and Sparling, 2004) were concerned with the negative effects of long-duration exercise and did not take into account the positive effects of shorter duration, sub-maximal exercise on cognition. As can be seen in Chapter 3, he is examining the possibility, he would probably say the likelihood, that positive effects of moderate intensity exercise on cognition are due to the tasks being simple and/or implicitly learned. It is dubious as to what extent this can account for some of the findings of Davranche and colleagues (Davranche, Audiffren and Denjean, 2006a), who used central executive tasks. A possible explanation, along similar lines to hypofrontality theory, is that there is competition between the cognitive, motor and emotional areas of the brain but it is not an 'all or nothing' interaction. This is similar to the ideas of Miller and Cohen (2001). Whether one agrees with Dietrich or not, the idea that explicitly learned and implicitly learned information may be affected differently is an interesting one. We know that they are recalled differently (Gazzaniga, Ivry and Mangun, 2001), therefore there may be differing effects of exercise on performance of implicitly and explicitly learned tasks. How future research might attempt to solve these problems is discussed below.

Chronic exercise

Like research into the effect of acute exercise on cognitive function, early research examining the effect of chronic exercise was atheoretical. Indeed, some would say that, with a few notable exceptions, it remains that way today. Currently, no comprehensive theory has been proposed that is designed to explain explicitly why there should be a relation between chronic exercise training and cognitive function. Several hypotheses have been generated. For example, the executive-function hypothesis and several neurological-based hypotheses have been proposed

to account for observed exercise-induced differences in human cognitive performance and animal behaviour. However, none of these hypotheses meet the requirements for a comprehensive theory (Underwood, 1957). Missing for contemporary researchers is a common vantage point from which systematic research can be conducted. Presently, researchers draw upon theories developed in other fields of psychology or neurology to generate research questions. As a result, research findings continue to lack cohesiveness. Today, as was true over a decade ago (Tomporowski, 1997), some well-designed studies have found that chronic exercise benefits cognitive function while other equally well-designed experiments report null effects. Contemporary researchers continue to advance a 'scatter gun' approach to their work that is strong on the exercise science side and weak on the cognitive side of the exercise-cognition relationship. Human cognition reflects interactions among numerous processes (memory, perception, learning, problem solving, etc.); however, research on the effects of chronic exercise seems to be limited to only a few of these processes. Much needed is a theory that would help to explain why routine physical activity might benefit some processes more than others or why certain types of exercise would have more of an effect on cognitive function than others.

As we saw in Chapter 2, some attempt has been made to examine possible psychoneuroendocrinological rationales but with no success, so far. However, work examining brain-derived neurotrophic factor (BDNF) does show much promise and makes sense, as BDNF has neuroprotective qualities and acts as a neurotransmitter in the hippocampus. The electroencephalography (EEG) research of Hillman and colleagues (see Chapter 8) also provides a stepping stone to show possible cognitive neuroscience factors that might account for the beneficial effects of exercise. Since the emergence of the discipline of psychology in the late nineteenth century, there has been considerable, and sometimes acrimonious, discussion concerning the merits of employing biologically based measures to explain psychological constructs. Over the past century the pendulum has swung several times from one end of the mind–body continuum to other. The views of several authors of chapters in this text suggest that neuropsychological approaches to examining the relation between exercise and cognition may be more fruitful than the conceptual approaches of psychological constructs that have dominated mainstream psychology. Progress in neuropsychology over the past decade has been advanced markedly by the development of methods of measuring brain function, the decreased cost and increased availability of neuropsychological laboratory equipment, and the rapid growth of the number of graduate programmes designed to train neuropsychology researchers. The pendulum appears to have shifted toward biological explanations of human behaviour and away from the use of psychological constructs. As discussed in some detail by Acevedo and Ekkekakis (2006), it will be important, however, to retain the view that advances in exercise psychology will benefit from a unified approach which stresses the convergence of neuropsychology findings and behavioural data.

16.2 Summary of research results

Acute exercise

Research results have not fully supported any theory. Simple tasks have tended to either not be affected by exercise or to show an improvement even at high intensities. Complex, central executive tasks, on the other hand, have shown a tendency to display disruption during high intensity exercise with no effect of moderate intensity exercise, although Davranche, Audiffren and Denjean (2006a) have shown positive effects of moderate intensity exercise on the performance of central executive tasks.

As pointed out in Chapter 4, the failure to demonstrate unequivocal results is complicated by research design problems. Undoubtedly the quality of research designs has improved dramatically since Tomporowski and Ellis' (1986) paper but we have probably all been guilty of making some, if not many, of the errors pointed out by Tomporowski in Chapter 4. While some of the weaknesses are due to poor scientific methods, others are more the result of practical problems when undertaking such research. Getting sufficient subjects for an experiment is a simple example. If you reduce what you are asking the people to do down to its basic terms, why should they take part? What would the general public think if you said to them, 'I want you to ride a cycle ergometer until you cannot keep going any longer – Oh! By the way you may vomit. Then I want you to come back to the laboratory three other times and ride at different intensities, including to exhaustion. While doing this you will have to carry out some cognitive tests and we will stick needles into you from time to time.' As Tomporowski pointed out, only a certain type of person is willing to do this, hence the difficulty in getting subjects, especially unfit ones, for research that attempts to compare the fit to the unfit.

Even where sample sizes are adequate there remain problems with the nature of the exercise protocols used. Most modern researchers, or certainly those that get published, take into account individual differences but there is still an amount of arbitrariness with regard to the exercise intensities chosen. Reading this book, however, you will undoubtedly have become aware that the nature of the cognitive tasks may be a more important factor. Most of the early researchers used choice reaction time as their cognitive test. The reason for this was based on information processing theory, the proponents of which saw the choice reaction time protocol as requiring the use of all of the brain's processes – perception, holding information in short-term memory, recalling information from long-term memory, making a decision and organizing the movement. They failed to understand that if the instructions to the participant were to press the appropriate button when a light was illuminated, there was no call on short-term memory, recall from long-term memory or decision-making. Thus, the task was far easier than hypothesized. This does not mean that such research was meaningless, far from it (we would say that because we have all done it at some time). The failure of such research to show the expected inverted-U effect led to attempts to find more difficult tasks to examine.

One of the recurring findings in this book is that the nature of cognitive tasks used has major implications on the results. It appears that comparatively simple tasks are more likely to show beneficial effects of exercise, while the more complex are more likely to be negatively affected by heavy exercise. However, the evidence is not unequivocal. There are undoubtedly issues with deciding what constitutes a complex task. Most researchers claim that central executive tasks are complex, activating large areas of the brain, in particular the prefrontal cortex. There is evidence for this (see Chapters 1–3), but there is no evidence from functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) studies to support the claims that *all* of the so called 'central executive' tasks do, in fact, activate the relevant areas of the brain. Moreover, recent research (Davranche, 2008) has suggested that, even for tasks where there is evidence that they activate the prefrontal cortex, the effect of exercise is not on all aspects of the tasks. Thus, the possibility that exercise positively and/or negatively affects different aspects of the same task requires further research. Furthermore, the possibility that within the same task there are positive effects on one aspect, *but* negative on another factor is a possibility. If this is occurring, one might see no outcome effect but a processing one.

Chronic exercise

Research into the chronic effects of exercise on cognitive function was given a tremendous boost by a publication in the journal *Nature*, which reported that routine aerobic activity benefited older adults' cognitive function (Kramer *et al.*, 1999). A subsequent meta-analysis of exercise research conducted with older adults provided additional support for the view that physical activity is beneficial for a variety of mental processes in older adults and that it is particularly effective in processes that constitute executive function (Colcombe and Kramer, 2003). Subsequent findings tend to support the 'executive function' hypothesis in older adults (see Chapter 12) and overweight children (see Chapter 13). Yet, several well-controlled, randomized experiments conducted with older adults have consistently failed to provide evidence for a relationship between aerobic exercise and older adults' cognitive function (Blumenthal *et al.*, 1989; Blumenthal *et al.*, 1991; Hill, Storandt and Malley, 1993; Hoffman *et al.*, 2008). The bases for these inconsistencies need to be addressed.

Numerous general articles published in mainline newsprint have extolled the psychological benefits of physical activity and the possibility that exercise may be able to lead to improvements in mental function, improve academic performance, and offset the effects of Alzheimer's disease and other neurodegenerative conditions. It will behove the academic community to be cautious not to be caught up in the limelight. The history of psychology is replete with numerous cases in which faddish treatments are rapidly adopted by the general public on the basis of little empirical evidence. Typically, these treatment fads have met with little success and, in the long run, inhibited systematic academic progress. Clearly, exercise as a 'treatment' will not be a 'cure all'. It will be important for research scientists to remain cautious concerning the exercise–cognition interaction. Much more needs to be learned

concerning how environmental factors (i.e. the intensity, duration and frequency of chronic exercise treatments) and individual difference factors (age, gender, personality, intelligence) moderate or mediate the effects of physical activity and systematic exercise on cognitive function.

16.3 Future theoretically driven research

Acute exercise

As Audiffren stated in Chapter 1, an inter-disciplinary rationale is the best way to explain the effect of acute, and indeed chronic, exercise on cognition. The starting point for such a theory could be the cognitive-energetic theories, particularly that of Sanders (1983). The roles of arousal, activation and effort outlined in this theory can be linked to cognitive neuroscience and, even, neuroendocrinology. Effort can be explained with regard to activation of brain areas, while arousal and activation are linked to hormonal and neurotransmitter changes. However, formulating such a theory is difficult for a number of reasons. First of all, many of the disciplines, which one would expect to be part of an inter-disciplinary approach, are comparatively new and, perhaps more importantly, are heavily dependent on technology. Cognitive neuroscience rationales are difficult to prove because the technology is limited. We have not yet seen anyone running on a treadmill while inside a fMRI scanner. Even using EEG is difficult when exercising. As we saw in Chapter 2, we still rely heavily on animal studies for explanations of the psychoneuroendocrinological effects of exercise in the brain. Moreover, exercise scientists are still learning about the nature of exercise. The notion that exercise is the same as other stressors looks simplistic now, but is an idea that we suspect all of us have had at some time or other. Furthermore, the study of the nature of exercise is showing that different types of exercise can induce very different biochemical responses. All of which makes our job the more difficult, but the more challenging and interesting.

Research examining how, and indeed if, different types of exercise affect cognition differently may afford us a greater insight into the exercise–cognition interaction. As we know more and more about the biochemical responses to exercise such research can be taken with greater experimental control than much of the earlier research. The very small amount of research that has examined the role of dehydration and exercise also needs to be developed. The question of whether dehydration is the key factor or whether dehydration adds to the stress remains.

Pesce pointed out in Chapter 11 that individual differences may well affect the exercise–cognition interaction. This is a very under-researched area. Some attempts have been made to examine fitness effects, but one must question the extent to which the 'unfit' subjects really are unfit or certainly sedentary. McMorris and Keen (1994) recruited unfit participants; they were really unfit as can be seen by their low maximal power outputs, however they were not truly sedentary. All participants actually

exercised occasionally and most played team games with their friends from time to time. Getting truly sedentary individuals proved impossible as they simply would not take part. The fact that the 'unfit' subjects actually carried out some physical activity, albeit occasionally, could have affected results. They demonstrated a negative effect during maximal intensity but no effect during moderate intensity exercise. Would this have happened had they been truly sedentary?

With some notable exceptions (Pesce *et al.*, 2007a; Minshull *et al.*, 2007), little attempt has been made to examine age and gender effects. Intuitively, one might expect issues such as trait anxiety, impulsivity and Type I personality traits, among many others, to affect the exercise–cognition interaction. Also cognitive styles may have an effect. Field-independent individuals may well be able to dissociate themselves from the negative aspects of exercise at high intensities while field-dependent persons may not. Similarly, one would expect augmenters to perceive the exercise as being harder than it is perceived by reducers, which might affect performance during heavy exercise.

Not only have individual differences not been examined, they have not been considered as factors involved in developing a theory. This is surprising, as many authors have cited Humphreys and Revelle's (1986) theory, which includes personality and motivation as key issues in the stress-performance interaction. Similalry, Kahneman (1973) stated that issues such as evaluation of task demands would influence the allocation of resources. McMorris (2006) included some of Kahneman's ideas in a tentative presentation of a possible model, however the model was still limited in its scope. We believe that an inter-disciplinary theory or model should be developed with input from cognitive psychologists, neuroscientists and exercise biochemists. The cognitive-energetics models may well be a good starting point as the other disciplines can explain many of the issues raised by the cognitive-energetic theorists.

Chronic exercise

Attempts to find psychoneuroendocrinological and neurological rationales for a chronic exercise–cognition interaction are commendable, but we need to spend some time working out a theoretical rationale for such an effect. How and why should there be any effect? The possibility that exercise-induced increases in concentrations of BDNF have a neuroprotective effect on the elderly is worth serious consideration. While exercise-induced increases in BDNF and other nerve factors in children, particularly in the hippocampus, may have beneficial effects on learning and memory. We need also to determine whether exercise is any better or worse than other factors, for example keeping the mind active, in maintaining cognitive function in the elderly. As for acute exercise, it seems very promising to examine the interaction of chronic exercise with some individual variables such as genetic polymorphisms (e.g. catechol-O-methyltransferase [COMT] Val158 Met polymorphisms) or level of education. There is also a need to examine the relative effects of differing exercise intensities, duration and frequency.

16.4 Future applied research

Acute exercise

In Parts 2 and 3 of this book, we examined several factors including implications for the exercise and cognitive function interaction. Although much of the research in this area has come from sports science departments, little is sports specific. In Chapter 9 we examined some of the implications for team games that require much in the way of decision-making. In that chapter, we raised the idea, or rather repeated Wade's (1967) idea, that practising while physically stressed may help the performer in the later stages of a game. A similar recommendation could be made to the military, where personnel have to make life and death decisions following and during heavy physical exertion. At this moment in time, there is no proof that his will be successful, but theoretically it makes sense. The idea that exposure to a stressor lessens its effect is an old one. We also pointed out in Chapter 5 that attempting to maintain euhydration will be beneficial in such circumstances. There is some support from the research for this claim but much more is needed, particularly in activity that is ecologically valid to the participants (military or sports people).

Not only do the exercise intensities and types need to be more ecologically valid, it makes sense to use cognitive tasks that are ecologically valid. Highlighting the nature of the tasks in terms of 'information transfer', short-term memory or central executive may be too simplistic. A well-learned task may be affected differently to a novel one regardless of its type. Research examining implicit learning and the effects of emotionally induced stress (Masters, 1992) has shown that implicitly learned tasks withstand greater stress than explicitly learned ones. Research comparing the effect of exercise on explicitly and implicitly learned tasks could be a good vehicle to help us determine the extent to which exercise acts the same as other stressors.

Chronic exercise

From the point of view of practical implications, those relating to health and aging are the most compelling. That there are positive results of exercise on cognition, and indeed psychological well-being, in the elderly is undeniable, but not unequivocal. Moreover, we still do not fully understand how this happens. From the point of view of the man/woman in the street it does not really matter. It works 'so let's do it'. However, for scientists there is a need to find out. Not just for interest's sake but also understanding the process allows us to better understand several factors related to the brain/body interaction. So far researchers cannot rule out the possibility that undertaking exercise is no better than a person taking an interest in any activity – music, crosswords, reading, and so on. However, as we saw in Chapters 3 and 8, there is a prima facie case for psychophysiological responses linked to improved cognitive function. One could make similar claims for the effects of exercise on children and, in particular, those with problems of obesity and attention deficit hyperactivity disorder (ADHD).

16.5 General summary

The roots of contemporary psychology can be traced to antiquity; however the history of psychology is relatively recent (Hergenhahn, 1992). Likewise, the belief that exercise is good for the mind was espoused as early as the fourth century BC; but the academic study of exercise's effects on mental function has emerged only quite recently. Indeed, only two decades ago a review of the available research led to the conclusion that exercise had little effect on cognitive function (Tomporowski and Ellis, 1986). Research conducted during the past decade has, however, led to a different interpretation of the exercise–cognition relationship. Several well-designed experiments have shown that both acute bouts of exercise and chronic exercise training influence specific aspects of cognitive function. While these recent studies have advanced our knowledge, there remains the need to be cautious; there are many unanswered questions concerning the exercise–cognition interaction. We hope that the information presented in this book will energize researchers to conduct studies that will solidify (or not) whether physical activity modifies the manner in which humans think and adapt to an ever changing world.

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