Breakfast consumption, breakfast composition and exercise: the effects on adolescents’ cognitive function

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BREAKFAST CONSUMPTION, BREAKFAST COMPOSITION AND EXERCISE: THE EFFECTS ON ADOLESCENTS’ COGNITIVE FUNCTION

by

Simon B. Cooper

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

September 2011

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ABSTRACT

The studies described in this thesis were undertaken to examine the factors affecting adolescents’ cognitive function across the school morning. Specifically, the effects of breakfast consumption, breakfast glycaemic index (GI) and a mid-morning bout of exercise were examined, whilst the final experimental chapter examined their combined effects.

The battery of cognitive function tests used in the present study was administered via a laptop computer and took approximately 15 min to complete. Across all experimental chapters, the visual search test (assessing visual perception), the Stroop test (assessing attention) and the Sternberg paradigm (assessing working memory) were used. Furthermore, in chapter V the Flanker task (also assessing attention) was added to the testing battery.

The first experimental study (chapter IV) examined the effects of consuming a self-selected breakfast on cognitive function, compared to breakfast omission. Ninety-six adolescents (12 to 15 years old) completed two experimental trials (breakfast consumption and breakfast omission), scheduled seven days apart, in a randomised crossover design. Following breakfast consumption, accuracy on the more complex level of the visual search test was higher than following breakfast omission ($p = 0.021$). Similarly, accuracy on the Stroop test was better maintained across the morning following breakfast consumption when compared with breakfast omission ($p = 0.022$). Furthermore, responses on the Sternberg paradigm were quicker later in the morning following breakfast consumption, on the more complex levels ($p = 0.012$). Breakfast consumption also produced higher self-report energy and fullness, lower self-report tiredness and hunger, and higher blood glucose concentrations, compared with breakfast omission (all $p < 0.001$). Overall, the findings suggested that breakfast consumption enhanced adolescents’ cognitive function, when compared with breakfast omission.

The second experimental study (chapter V) examined the effects of consuming a high GI breakfast, a low GI breakfast and breakfast omission on cognitive function. Forty-one adolescents (12 to 14 years old) completed three experimental trials, each scheduled seven days apart, in a randomised crossover design. There was a greater improvement in response times across the morning following a low GI breakfast, compared to breakfast omission on the complex level of the Stroop test ($p = 0.009$) and both levels of the Flanker task ($p = 0.041$), and compared to following a high GI breakfast on the complex level of the visual search test ($p = 0.025$) and all levels of the Sternberg paradigm ($p = 0.013$). Furthermore, accuracy was enhanced following a low GI breakfast, compared to breakfast omission on the more complex levels of the visual search test ($p = 0.032$), Sternberg paradigm ($p = 0.051$) and Flanker task ($p = 0.001$), and compared to following a high GI breakfast on both levels of the Stroop test ($p = 0.033$) and the more complex levels of the Sternberg paradigm ($p = 0.002$) and Flanker task ($p = 0.014$). Furthermore, participants exhibited a lower glycaemic response following the low GI breakfast ($p < 0.001$), though there was no difference in the insulininaemic response ($p = 0.063$), compared to following the high GI breakfast. Overall, the findings suggest that a low GI breakfast is the most beneficial for adolescents’ cognitive function, compared with a high GI breakfast and breakfast omission.
The third experimental study (chapter VI) examined the effects of a mid-morning bout of exercise, following a self-selected breakfast, on cognitive function. Forty-five adolescents (12 to 13 years old) completed two experimental trials (exercise and resting), scheduled seven days apart, in a randomised crossover design. There was a greater improvement in response times across the morning following the mid-morning bout of exercise on all levels of the Sternberg paradigm \( (p = 0.010) \). There was also a greater improvement in response times across the morning on the visual search test following the exercise \( (p = 0.009) \), but this improved speed was combined with a greater decrease in accuracy following the exercise \( (p = 0.044) \). This suggests that following exercise, the adolescents exhibited a speed-accuracy trade-off, whereby they responded quicker, but this was to the detriment of accuracy. Overall, the findings suggest that whilst the mid-morning bout of exercise improved some components of cognitive function (e.g. response times on the Sternberg paradigm), it did not affect other components (e.g. Stroop test performance).

The final experimental study (chapter VII) examined the combined effects of breakfast GI and a mid-morning bout of exercise on adolescents’ cognitive function. Forty-two adolescents (11 to 13 years old) were allocated to matched high GI \( (n = 22) \) and low GI \( (n = 20) \) breakfast groups. Within the matched groups, participants completed two experimental trials (exercise and resting) in a randomised, crossover design. The findings indicate that, for the complex level of the Stroop test, following the high GI breakfast there was a greater improvement in response times across the morning on the resting trial, whereas following the low GI breakfast response times improved across the morning on both the exercise and resting trials, though the magnitude of the improvement was greatest on the exercise trial \( (p = 0.012) \). On the Sternberg paradigm, response times improved across the morning following the low GI breakfast regardless of exercise, whereas following the high GI breakfast response times improved across the morning on the exercise trial, though remained similar across the morning on the resting trial \( (p = 0.019) \). Overall, the findings suggest that the effects of the mid-morning bout of exercise were dependent upon the breakfast GI and the component of cognitive function being examined and that, for the Stroop test, the beneficial effects of the low GI breakfast and mid-morning bout of exercise were additive.

Overall, the results from this thesis suggest that breakfast consumption is more beneficial than breakfast omission and more specifically, that a low GI breakfast is more beneficial than both a high GI breakfast and breakfast omission, for adolescents’ cognitive function across the school morning. However, the effects of exercise appear to be more variable, with the effect of exercise depending upon the component of cognitive function examined and the GI of the breakfast consumed. Overall, the findings presented in this thesis suggest that the nutritional effects on adolescents’ cognitive function (i.e. the effects of breakfast consumption and GI) were stronger and more consistent than the exercise induced effects.

**Keywords:** Adolescents; Cognitive Function; Breakfast Consumption; Breakfast Glycaemic Index; Exercise
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There are a number of people without whom I would have been unable to undertake the work that is completed in this thesis.

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Preface

Unless otherwise indicated by reference to published literature or acknowledgement, the work contained within this thesis is that of the author and has not been previously submitted for another degree to this or any other university.

Some of the work presented in this thesis has been published, or is in press, as follows:

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7.7 Blood lactate concentration across the morning following the high GI and low GI breakfasts, on the exercise and resting trials
Chapter I

Introduction

Cognitive function is defined as a term used to describe a ‘great variety of brain mediated functions and processes’ and has been split into six main components; memory, attention, perception, psychomotor, language and executive functions (Schmitt et al, 2005). Therefore, a general definition of cognitive function is ‘the functioning of the brain’, thus it is not surprising that cognitive function has often been linked to academic and scholastic achievement. Due to the effects of cognitive function on academic achievement, cognitive function and the factors affecting it are of primary importance during adolescence (especially when completing assessments and examinations at school), when academic achievement and examination grades are seen as important by parents, teachers and the adolescents themselves.

A number of factors are believed to affect cognitive function, including: arousal, mood, motivation, and physical well-being (Schmitt et al, 2005). Furthermore, it has also been suggested that nutrition can affect cognitive function (Isaacs & Oates, 2008), with one area that has received particular attention being the effects of breakfast consumption. Indeed, it is often stated that breakfast is the most important meal of the day. However, evidence suggests that young people are more likely to skip breakfast than any other meal (Dwyer et al, 2001), with data from Mahoney et al (2005) suggesting that only just over 50% of children (aged 6 to 11) regularly eat breakfast. Furthermore, breakfast skipping in children and adolescents is reported to be increasing in prevalence (Siega-Riz et al, 1998). This is of particular concern because regular breakfast consumption is reported to have a number of
positive effects in young people including; improving dietary adequacy, a decreased risk of being overweight or obese and improved cognitive function (Pearson et al, 2009).

Some of the work examining breakfast consumption and cognitive function in adults dates back over half a century, when a series of experiments were conducted by Tuttle and colleagues, collectively termed the Iowa breakfast studies (e.g. Tuttle et al, 1949). Whilst showing beneficial effects of breakfast consumption, these studies were limited to relatively simple measures of cognition (simple and choice reaction time tasks) and employed only small numbers of participants. These studies were however instrumental in stimulating further work in the area, with subsequent findings showing beneficial effects of breakfast on a number of components of cognitive function, including memory and attention, in adults (for review see Gibson & Green, 2002) and children (Hoyland et al, 2009). There is also some sparse evidence to suggest that breakfast consumption is beneficial for cognitive function in adolescents, with memory enhanced following a prescribed breakfast, when compared to breakfast omission (Widenhorn-Müller et al, 2008). However, other studies have found no effects of breakfast consumption on cognitive function in adolescents, but employed cross-sectional study designs (Dickie & Bender, 1982) or compared breakfast consumption with consumption of a very low energy breakfast (Cromer et al, 1990). In their review, Hoyland et al (2009) therefore concluded that the effects of breakfast consumption on cognitive function in adolescents require further research.

Another factor implicated in both the health and cognitive benefits of breakfast consumption is the composition of breakfast, including an examination of the glycaemic index (GI). Glycaemic index refers to the effect of a food on postprandial glycaemia, with high GI foods producing a higher peak glucose concentration and greater overall glycaemic response than low GI foods (see section 2.2.4 for full explanation of GI). The health benefits
of a low GI diet are well established (Livesey, 2008) and include a lowered risk of non-insulin-dependent diabetes mellitus (Meyer et al, 2000) and coronary heart disease (van Dam et al, 2005), as well as a decrease in risk markers for both conditions (Frost et al, 1999; Liese et al, 2007).

A low GI breakfast has also been suggested to improve cognitive function, when compared to a high GI breakfast, in both adults (for example, enhanced memory in the study of Benton et al (2003)) and children (for example, enhanced memory and attention in the study of Mahoney et al (2005)). However, the effects of the GI of breakfast on cognitive function in adolescents appear more equivocal, in that a low GI breakfast was most beneficial for working memory and attention in the study of Wesnes et al (2003), whereas a high GI breakfast was most beneficial for enhanced verbal episodic memory in the study of Smith & Foster (2008). There are numerous explanations for these differences, including measuring different components of cognitive function, testing at different times relative to breakfast consumption and the use of varying high and low GI breakfasts (including those which were not matched for key variables such as energy and macronutrient content). Therefore, clarification of the effects of breakfast GI on cognitive function in adolescent populations is clearly an area which warrants further research.

It has also been suggested that exercise exhibits both chronic and acute effects on cognitive function (Etnier et al, 1997). In terms of the chronic effects, it has been suggested that enhanced physical fitness is beneficial for cognitive function in adults and young people (Etnier et al, 2006; Castelli et al, 2007). In terms of the acute effects, several reviews of the evidence in adults have concluded that exercise enhances cognitive function (Brisswalter et al, 2002; Tomporowski, 2003). However, less work has examined the acute effects of exercise on cognitive function in young people. Some studies have suggested that cognitive
function is enhanced during exercise (Brisswalter et al, 2002), but in everyday school settings, the effects of a bout of exercise (i.e. a PE lesson or break time) on subsequent cognitive function (i.e. in the next academic lesson 30-60 min later) is of greater importance for academic achievement than cognitive function during the exercise itself. There is some evidence to suggest that exercise can enhance subsequent attention (Budde et al, 2008) and mathematical computation (Travlos, 2010) in adolescents, whilst other studies have shown no beneficial effects of exercise on attention in adolescents (Stroth et al, 2009). Furthermore, several meta-analyses, based largely on unpublished studies, have found a beneficial effect of exercise on adolescents’ cognitive function (Etnier et al, 1997; Sibley & Etnier, 2003). However, overall conclusions are difficult to make due to multiple components of cognitive function being measured and the use of different modes, durations and intensities of exercise, as well as the meta-analyses providing limited details of the unpublished studies included in their analysis. Therefore, it is clear further research is required to examine the effects of exercise on subsequent cognitive function, which is of particular importance in adolescents.

Whilst studies in the literature to date have considered the effects of breakfast consumption, breakfast composition and exercise individually, in everyday settings these factors are likely to interact to affect cognitive function during the morning. Therefore, it is important that the combined effects of these factors are considered, a void in the literature that this thesis aims to address.

Therefore, the purpose of this thesis is to test a number of hypotheses relating to cognitive function in adolescents:

- Breakfast consumption, when compared to breakfast omission, will be beneficial for adolescents’ cognitive function.
• A low glycaemic index (GI) breakfast will be the most beneficial for adolescents’ cognitive function, when compared to a high GI breakfast and breakfast omission.

• Completing a mid-morning bout of exercise will be beneficial for adolescents’ cognitive function, when compared with continuing to rest.

• Finally, the combined effects of the GI of breakfast and a mid-morning bout of exercise will be examined, to establish whether there is an optimal combination of breakfast GI and exercise for adolescents’ cognitive function.

The following eight chapters document this work. Chapter II provides a review of the literature and describes what is currently known regarding the effects of breakfast consumption, breakfast composition and exercise on adolescents’ cognitive function. The general methods used throughout the studies included in this thesis are described in chapter III. The subsequent four chapters provide the details of each of the individual studies conducted. Chapter IV examines the effects of breakfast consumption, compared to breakfast omission, on adolescents’ cognitive function. Chapter V examines the effects of breakfast GI on adolescents’ cognitive function. Chapter VI examines the effects of a mid-morning bout of exercise, whilst chapter VII examines the combined effects of breakfast GI and a mid-morning bout of exercise on adolescents’ cognitive function. Chapter VIII discusses the main findings of the four experimental studies and draws overall conclusions regarding the effects of breakfast consumption, breakfast composition and exercise on adolescents’ cognitive function across the morning. Finally, some directions for future research are suggested.
Chapter II

Review of Literature

2.1: Definition of Terms

Throughout this thesis, a number of specific terms will be used and for the purposes of clarity, definitions of these terms are provided in this section. The concept of cognitive function will be introduced and consideration will be given to its measurement and importance for academic achievement. The term adolescents will be defined, and the reasons for the focus upon adolescents in this thesis provided. Although it is an everyday term, breakfast will then be defined, followed by an explanation of glycaemic index and glycaemic load, and finally, definitions of physical activity and exercise will be provided.

2.1.1: Cognitive Function

2.1.1.1: Definition of Cognitive Function

Cognitive function has been defined as ‘a general term covering all the various modes of knowing – perceiving, remembering, imagining, conceiving, judging and reasoning’ (Drever, 1952). More recently, cognitive function has been defined as ‘a term used to describe a great variety of brain-mediated functions and processes’ (Schmitt et al, 2005). Therefore, although no universal definition of cognitive function is available, broadly it refers to the functioning of the brain. More specifically, Schmitt et al (2005) propose that cognitive function includes six, inter-related, components, as illustrated in figure 2.1.
The model suggests the six main components of cognitive function are; memory, attention, perception, psychomotor, language and executive functions (Schmitt et al, 2005). These components can be further divided into sub-components, for example memory can be split into short- and long-term memory, as well as by the mode of information processed (e.g. verbal, visual and auditory), whilst attention can also be similarly sub-divided according to the mode of information to be processed. Whilst the six components appear separately on the model, effective cognitive functioning depends on these components working together efficiently. For example, it would not be possible for information to be processed and stored in an individual’s memory, without first attending to the appropriate information from the environment (attention), or indeed perceiving such information from the environment (perception).
2.1.1.2: Assessment of Cognitive Function

When assessing the effects of various interventions (e.g. diet and exercise) on cognitive function, the measurement of cognitive function is obviously key. The issue of neuropsychological assessment is considered in great detail by Lezak et al (2005), and is beyond the scope of this thesis. However, several points are important to consider, which will be reviewed in this section.

Primarily, it is important to measure a component of cognitive function believed to be susceptible to the intervention (Schmitt et al, 2005). For example, memory has been shown to be susceptible to changes in blood glucose (e.g. Benton & Sargent, 1992), thus studies employing interventions which affect blood glucose concentrations (e.g. breakfast consumption) should include a measure of memory. However, it has also been suggested that a battery of cognitive function tests should be used (Westenhoefer et al, 2004; Schmitt et al, 2005), due to the interacting nature of the different components of cognitive function. Therefore, utilising a battery of tests allows the greatest claims to be made regarding the effects on cognitive function (Westenhoefer et al, 2004). A further important consideration to be made is to ensure the difficulty of the cognitive function tests selected is appropriate for the study population. If the tests are not appropriate for the study population, floor and ceiling effects may be evident, reducing the sensitivity of the tests to the expected improvement or impairment in performance (Schmitt et al, 2005). Inappropriate test difficulty may also lead to boredom or frustration affecting motivation, which in turn affects the outcome of the tests.

Within the tests of cognitive function selected, it is also important to measure both the speed and accuracy of responses (Schmitt et al, 2005). This is because if an improvement in one parameter is seen (e.g. response speed), but this is to the detriment of the other parameter (e.g. response accuracy), concluding an overall improvement in cognitive function may give
a false impression. Furthermore, due to the improvement in performance seen with repeated measures on cognitive function tests (commonly termed ‘learning effects’) (Wilson et al, 2000), it is important that participants in studies are familiarised with the tests to be used prior to the start of the study. In addition, to avoid warm-up effects (temporary poorer performance at the start of a test) (Adams, 1961), it is suggested that ‘dummy stimuli’ (stimuli for which the data are discarded) are included (Schmitt et al, 2005).

In addition to the above considerations regarding the cognitive function tests, the selection of participants and the conditions in which they complete the tests are also important. A homogenous sample of participants (for example, with regards to age) is optimal, reducing potential confounding variables in studies and allowing specific statements regarding the findings to be made (Schmitt et al, 2005). Furthermore, the environmental conditions (e.g. lighting and sound) should be controlled (especially in studies employing repeated measures), as well as some level of control over participants diet and physical activity prior to the tests, given that all these factors may affect performance on the cognitive function tests (Schmitt et al, 2005) and thus confound study outcomes if they are not controlled for appropriately.

2.1.1.3: Importance of Cognitive Function

As cognitive function can broadly be defined as ‘the functioning of the brain’, it is unsurprising that cognitive function and academic achievement are often considered related principles (e.g. Pollitt & Matthews, 1998). This association is logical considering a practical example – if a young person is in an academic lesson and displays improved cognitive function (i.e. perception - receiving information from the environment, attention - being able
to focus on this information, and memory - being able to store this information), it is logical that this young person will learn more and display enhanced academic achievement. Indeed, many long-term studies have assessed the effects of regular breakfast consumption or participation in physical education classes on academic achievement (Grantham-McGregor, 2005; Coe et al, 2006; Ahamed et al, 2007). However, the focus of this thesis is on cognitive function and the factors which exhibit an acute effect on it.

2.1.2: Adolescents

The focus of this thesis is on ‘adolescents’, therefore it is imperative that this term is defined and the reasons for this focus made clear. The definition and classification of the early stages of the human lifespan have been the focus of much interest in the literature, though it is still an area of some controversy. The most universally accepted definitions are provided by Bogin (1999), and are represented in figure 2.2.

Figure 2.2: Classification of the early years of the human lifespan (redrawn from Bogin (1999))
Specifically, adolescence refers to the five to ten years after the onset of puberty, with puberty defined as ‘an event of short duration at the end of the juvenile stage, characterised by dramatic increases in sex hormones’ (Bogin, 1999). In terms of chronological age, adolescence usually begins at the age of 10 in girls and 12 in boys, though there is significant variation between individuals (Bogin, 1999; Cameron, 2002). Despite the common use of chronological age, it is important to acknowledge the wide variety of measures available to assess maturity and thus define adolescents (e.g. skeletal wrist X-rays and secondary assessment of sexual characteristics). However, due to the practical limitations in the school-based studies conducted in this thesis (and the literature to date), chronological age will be used to define ‘adolescents’, and participants aged 11 to 16 will be classified as ‘adolescents’. Furthermore, the term ‘children’ will be used to refer to participants under the age of 11, and ‘young people’ will refer to children and adolescents collectively.

Adolescents are the focus of this thesis because as a population they are underrepresented in the literature to date examining the effects of both diet (especially breakfast) and exercise on cognitive function, whilst the effects in younger children and adults are more frequently reported (Hoyland et al, 2009; Keeley & Fox, 2009). Despite the lack of research in this age group, it has been suggested that adolescents are particularly worthy of study in this area for three main reasons. Firstly, adolescents are undergoing rapid growth and changes in metabolism (see above), thus their responses may be different to those of younger children (Cromer et al, 1990; Kanarek, 1997). Secondly, it has been reported that younger children (3-11 years old) have a larger brain weight relative to their body weight and a 50% greater metabolic rate per unit of brain weight, thus generalising the findings in younger children to adolescents is not recommended (Hoyland et al, 2009). Thirdly, the academic work completed by adolescents is of a greater complexity and academic achievement is of
paramount importance during adolescence (Cromer et al, 1990). Thus, should cognitive function (and consequently, academic achievement) be affected by diet and/or exercise during adolescence, a number of different groups (the adolescents themselves, parents/carers, schools and policy makers) would be interested in trying to modify such factors to optimise cognitive function (and consequently learning and academic achievement) during this critical time.

2.1.3: Breakfast

Breakfast, as the name suggests, literally means to break the overnight fast, and is most easily defined as the first meal of the day. In the studies which are reviewed and compared in this thesis, a wide range of breakfasts have been provided. However, the term ‘breakfast’ consistently refers to food and/or drink consumed in the morning, either at home or upon arrival at school (depending on the study design). It has also been suggested that the food and drink should consist of a minimum energy content to classify as ‘breakfast’. However, often the energy content of the breakfast has not been reported in earlier studies. Therefore, in this thesis, ‘breakfast’ refers to food and/or drink consumed in the morning to ‘break’ the overnight ‘fast’.

2.1.4: Glycaemic Index

The concept of glycaemic index (GI) was proposed by Jenkins et al (1981) and is a measure of the quality of the carbohydrate. GI classifies foods according to their effect on postprandial glycaemia (blood glucose responses after consuming 50 g of available carbohydrate from the food), when compared to 50 g of available carbohydrate from a
reference food (typically white bread). Per gram of carbohydrate, foods with a high GI result in higher peak blood glucose concentrations and a greater overall glycaemic response in the two hour postprandial period (as determined by incremental area under the curve (IAUC) (Wolever & Jenkins, 1986)) than low GI foods (Wolever & Bolognesi, 1996). Specifically, GI is calculated as follows:

\[
GI = \frac{\text{IAUC for 50 g carbohydrate from test food}}{\text{IAUC for 50 g carbohydrate from white bread}} \times 100
\]

(adapted from Wolever & Jenkins (1986))

Originally, GI only applied to single foods, but since its introduction a method to calculate the GI of mixed meals (meals containing more than one food) has been developed (Wolever & Jenkins, 1986). When examined, this method produced excellent agreement with determination via calculation of IAUC for four different meals \((r = 0.987, p < 0.02)\) (Wolever & Jenkins, 1986), and thus is widely used and accepted as a valid method for the calculation of the GI of mixed meals.

The similar, related, concept of glycaemic load (GL) was introduced by Salmeron et al, 1997). Glycaemic load is a measure of both the quality and quantity of carbohydrate and is calculated as follows:

\[
GL = \frac{\text{GI} \times \text{Amount of available carbohydrate}}{100}
\]

(adapted from Salmeron et al (1997))

It is recommended that both GI and GL are used in conjunction to describe the glycaemic potency of a meal or food (ADA, 2004). Indeed, the GI and GL values of large numbers of foods have been reported in the literature and are commonly used as reference values (Foster-Powell et al, 2002; Henry et al, 2005; Henry et al, 2007). In the experimental
studies presented in this thesis, GI is used to classify the breakfasts. However, given that the carbohydrate content of the breakfasts is matched, the high GI breakfast is also high GL, and the low GI breakfast is also low GL, given the inter-related nature of GI and GL.

2.1.5: Physical Activity and Exercise

It is important that these inter-related concepts are clearly defined. Physical activity is defined as ‘any bodily movement produced by skeletal muscles that results in energy expenditure’ (Caspersen et al, 1985). Exercise is defined as ‘a subset of physical activity that is planned, structured, and repetitive, done to improve one or more components of physical fitness’ (Caspersen et al, 1985). The terms physical activity and exercise are often used interchangeably, particularly in the literature surrounding cognitive function. In this thesis, the term ‘exercise’ will encompass both concepts as they are defined above and will focus on the acute effects of such exercise. A third, related concept is physical fitness, which is defined as ‘a set of attributes that are either health- or skill-related that relate to the ability to perform physical activity’ and includes components such as agility, balance, muscular endurance, muscular strength, power and speed (Caspersen et al, 1985).

2.2: The Effects of Breakfast Consumption on Cognitive Function

2.2.1: Adults

Although there are only a limited number of studies examining the effects of breakfast consumption, as opposed to breakfast omission, on cognitive function in adults, a review of the literature concluded that breakfast omission adversely affects adults’ cognitive function
(Gibson & Green, 2002). A series of early studies by Tuttle and colleagues, collectively termed the ‘Iowa breakfast studies’ were the first to demonstrate an effect of breakfast on adults’ cognitive function. For example, Tuttle et al (1949) showed that response times in 6 females (aged 22 to 27) were quicker following breakfast consumption, when compared to the breakfast omission condition. However, these studies are often criticised for having only a small number of participants and for being limited to very basic, reaction time based tasks. However, despite their limitations, these studies were instrumental in stimulating future research into the area.

Some 40 years after the Iowa breakfast studies, findings in a study employing 33 university students (aged 19 to 28) indicated that the speed of spatial and verbal memory was enhanced two hours following breakfast consumption, when compared to following breakfast omission (Benton & Sargent, 1992). Although accuracy on the memory tasks was not affected by breakfast consumption, the enhanced speed of memory allowed the authors to conclude that overall, breakfast consumption was beneficial for adults’ memory later in the morning. Furthermore, it has also been shown that breakfast consumption improved word recall (a measure of verbal memory) (Smith et al, 1994) and spatial memory (Smith et al, 1999). Interestingly, in these studies, a beneficial effect of breakfast consumption was only demonstrated for memory, whereas attention based tasks were unaffected.

2.2.2: Children

There has been greater interest in the literature regarding the effects of breakfast consumption on cognitive function in children, compared to the limited work which has been conducted in adults. In addition to the aforementioned reasons explaining why the responses
of children may be different to those of adults (section 2.1.2), a further reason for increased interest in children compared to adults is because a number of studies have examined the effects of government breakfast programmes aimed at school children (e.g. Chandler et al, 1995; Chang et al, 1996; Jacoby et al, 1996; Vaisman et al, 1996). However, such studies have tended to focus on the longer term effects of regular breakfast consumption on health and academic achievement, thus are beyond the scope of this thesis (for review see Grantham-McGregor, 2005).

However, complementing the work which has been conducted examining breakfast consumption and academic achievement, a number of studies have also examined the acute effects of breakfast consumption on cognitive function in children. A summary of the studies conducted in this area is provided in table 2.1. Comparisons between the studies which have been conducted in this area are difficult due to differences in; the components of cognitive function assessed (e.g. memory, attention, perception), the tests used to assess these components, the age group of the children studied, and the nature and timing of the breakfasts provided. However, this section will review the available evidence regarding breakfast consumption and cognitive function in children and draw conclusions as to what is currently known.

Generally, breakfast consumption has been shown to have a beneficial effect on cognitive function in children (Pollitt et al, 1981; Conners & Blouin, 1982; Pollitt et al, 1983; Busch et al, 2002; Benton & Jarvis, 2007). These effects are evident across a number of components of cognitive function, including memory (Wesnes et al, 2003; Mahoney et al, 2005) and attention (Conners & Blouin, 1982; Busch et al, 2002; Benton & Jarvis, 2007). Furthermore, as can be seen by examining table 2.1, the studies to date have assessed the
Table 2.1: A review of the studies examining the effects of breakfast consumption, as opposed to breakfast omission, on cognitive function in children

<table>
<thead>
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<th>Authors</th>
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<th>Age of Participants</th>
<th>Conditions</th>
<th>Tests</th>
<th>Variables Assessed</th>
<th>Timing of Tests</th>
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<td>9-11</td>
<td>BF &amp; NBF</td>
<td></td>
<td>Hagen Central Incidental Task MFFT</td>
<td>180 min post BF</td>
<td>Yes</td>
<td>NBF enhanced accuracy</td>
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<td>9-11</td>
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<td>Accuracy of problem solving</td>
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<td></td>
<td></td>
<td></td>
<td>Arithmetic test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pollitt et al (1983)</td>
<td>39</td>
<td>9-11</td>
<td>BF &amp; NBF</td>
<td>MFFT</td>
<td>Speed of problem solving</td>
<td>180 min post BF</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracy of problem solving</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Busch et al (2002)</td>
<td>21</td>
<td>9-12 (male only)</td>
<td>BF &amp; NBF</td>
<td></td>
<td>Speed of spatial memory</td>
<td>15 min post BF</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Map task</td>
<td>Accuracy of spatial memory</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Speed of verbal memory</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Story Recall</td>
<td>Accuracy of verbal memory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>n</td>
<td>Age of Participants</td>
<td>Conditions</td>
<td>Tests</td>
<td>Variables Assessed</td>
<td>Timing of Tests</td>
<td>Effect?</td>
<td>Findings</td>
</tr>
<tr>
<td>-------------------</td>
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<td>----------------------------</td>
</tr>
<tr>
<td>Busch et al (2002) cont.</td>
<td></td>
<td></td>
<td></td>
<td>CPT</td>
<td>Speed of attention</td>
<td></td>
<td>No</td>
<td>BF enhanced accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracy of attention</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rey complex figure copy &amp; recall test</td>
<td></td>
<td>No</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed of visual perception</td>
<td></td>
<td>No</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracy of visual perception</td>
<td></td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Benton &amp; Jarvis (2007)</td>
<td>20</td>
<td>9</td>
<td>Habitual BF or NBF</td>
<td>Observation of classroom behaviour</td>
<td>Time on task</td>
<td>11.15-12.15 (~240 min post BF)</td>
<td>Yes</td>
<td>BF increased time on task</td>
</tr>
</tbody>
</table>

n: number of participants in study; BF: breakfast consumption; NBF: breakfast omission; MFFT: matching familiar figures test; CPT: continuous performance test; WM: working memory
effects of breakfast consumption up to 4 h post breakfast, thus it appears that breakfast consumption enhances cognitive function in children across the morning.

Upon examination of table 2.1, it appears that accuracy is particularly affected by breakfast consumption, whereas speed (or response times) on the tests employed was either unaffected by breakfast consumption, or not measured. In the earlier scenario, with accuracy improved following breakfast whilst speed was unaffected, it may be concluded that breakfast consumption was beneficial for that particular component of children’s cognitive function. However, where speed was not measured and studies found an improvement in accuracy, the findings must be interpreted cautiously (e.g. Conners & Blouin, 1982) because the improvement in accuracy could have been the result of a speed-accuracy trade-off, whereby accuracy improved following breakfast consumption but as a result, participants responded slower. Therefore, concluding that performance improved just based on the improvement in accuracy could be misleading.

Whilst the literature suggests a general trend for an improvement in children’s cognitive function following breakfast consumption, it is also important to note that not all components of cognitive function examined in the aforementioned studies have yielded positive effects of breakfast consumption. For example, in the study of Busch et al (2002), whilst breakfast consumption was shown to have a beneficial effect on the accuracy of attention, there were no effects on spatial memory, verbal memory or visual perception. However, in the study of Busch et al (2002) the cognitive tests were completed only 15 min after breakfast. Therefore, the null findings could be because the effects of breakfast consumption did not become evident until later in the morning, a suggestion in line with a recent review suggesting that the positive effects of breakfast consumption on cognitive function become more evident later in the school morning (Hoyland et al, 2009). It must also
be noted that in one early study (Pollitt et al, 1981), the accuracy of working memory was actually enhanced following breakfast omission when compared to breakfast consumption. However, based on the weight of available evidence, it appears that this result is an anomaly and the authors suggested that the finding could be due to increased arousal associated with the extended fast, rather than breakfast omission per se (Pollitt et al, 1981).

Overall, the available evidence suggests that breakfast consumption, when compared to breakfast omission, enhances cognitive function in children. However, comparisons between the studies are difficult due to the wide ranging methodologies employed, the different components of cognitive function examined and the varied nature of the breakfasts provided. However, the ‘1995 international symposium on breakfast and performance in young people’ concluded that whilst it is difficult to draw any definitive conclusions, the data suggests that ‘omitting breakfast interferes with cognition and learning’ (Pollitt & Matthews, 1998). Furthermore, a more recent systematic review concluded that the evidence indicates that breakfast consumption is more beneficial than skipping breakfast for cognitive function in children, especially when cognitive performance is assessed later in the school morning (Hoyland et al, 2009).

2.2.3: Adolescents

Fewer studies to date have examined the effects of breakfast consumption, compared to breakfast omission, on cognitive function in an adolescent population. As previously mentioned, the metabolic and cognitive responses to breakfast are likely to be different between adolescents and both adults and children (see section 2.1.2); thus it is important that we examine the evidence available in these populations separately. Indeed, it was as early as
the 1950’s when one of the Iowa breakfast studies examined the effects of breakfast consumption on cognitive function in adolescents. The findings indicate that whilst breakfast consumption did not affect the objective measure of choice reaction time, subjectively school teachers reported improved attitude and school performance following breakfast consumption (Tuttle et al, 1954). However, as with the other Iowa breakfast studies, this study has been widely criticised for having small subject groups, using subjective measures and being limited to reaction time tasks (Smith et al, 1994).

Since this early work, only three studies have studied the effects of breakfast consumption on cognitive function in adolescents (Dickie & Bender, 1982; Cromer et al, 1990; Widenhorn-Müller et al, 2008), which are summarised in table 2.2. The earliest of these studies (Dickie & Bender, 1982) employed large numbers of adolescents ranging from 12 to 17 years old. The findings indicated that there was no difference in performance on a test of working memory or attention in those who habitually consumed or skipped breakfast, nor was there an effect of breakfast omission in regular breakfast consumers on the same measures (Dickie & Bender, 1982). However, the study employed a cross-sectional design, assessing participants after their usual breakfast habits and thus a range of confounding variables could have affected the study outcome. Furthermore, the study only assessed the accuracy of working memory and attention, and did not measure speed. In addition, some of the testing was conducted post-lunch, thus it would become very difficult to differentiate the effects of breakfast, from the effects of lunch, on cognitive function.

A further cross-sectional study examining breakfast and cognitive function in adolescents examined the effects of the administration of a standard government breakfast, in comparison with a very low energy (12 kcal) breakfast (Cromer et al, 1990). This study stemmed from the earlier work, reviewed by Grantham McGregor (2005), but focussed on
Table 2.2: A review of the studies examining the effects of breakfast consumption, as opposed to breakfast omission, on cognitive function in adolescents

<table>
<thead>
<tr>
<th>Authors</th>
<th>n</th>
<th>Age of Participants</th>
<th>Conditions</th>
<th>Methodology</th>
<th>Variables Assessed</th>
<th>Timing of Tests</th>
<th>Effect</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dickie &amp; Bender</td>
<td>227</td>
<td>12</td>
<td>Habitual BF habits (i.e. BF or NBF)</td>
<td>Sentence Verification Test</td>
<td>Accuracy of WM</td>
<td>240 &amp; 360 min post BF (pre &amp; post lunch)</td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td>(1982)</td>
<td>260</td>
<td>15</td>
<td>NBF in habitual BF eaters</td>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>108</td>
<td>16-17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>227</td>
<td>12</td>
<td>Habitual BF habits (i.e. BF or NBF)</td>
<td>Cancellation test</td>
<td>Accuracy of attention</td>
<td>180 &amp; 300 min post BF</td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>260</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
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<td>No</td>
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<tr>
<td></td>
<td>108</td>
<td>16-17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td>Cromer et al (1990)</td>
<td>34</td>
<td>14</td>
<td>Government BF (424 kcal) vs. very low energy (12 kcal) BF</td>
<td>Rey Auditory Visual Learning test (AVLT) CPT (target = '5') MFFT</td>
<td>Accuracy of WM Speed of problem solving Accuracy of problem solving</td>
<td>60 &amp; 240 min post BF</td>
<td>No</td>
<td>---</td>
</tr>
</tbody>
</table>

Chapter II: Review of Literature
<table>
<thead>
<tr>
<th>Authors</th>
<th>n</th>
<th>Age of Participants</th>
<th>Conditions</th>
<th>Tests</th>
<th>Variables Assessed</th>
<th>Timing of Tests</th>
<th>Effect?</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Widenhorn-Müller et al</td>
<td>104</td>
<td>13-20</td>
<td>BF &amp; NBF</td>
<td>LGT-3 test</td>
<td>Accuracy of visuospatial memory</td>
<td>Immediately post BF</td>
<td>Yes</td>
<td>BF enhanced accuracy</td>
</tr>
<tr>
<td>(2008)</td>
<td></td>
<td></td>
<td></td>
<td>d2 test</td>
<td>Accuracy of verbal memory</td>
<td></td>
<td>No</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total memory score</td>
<td></td>
<td>No</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed and accuracy of attention (number of correct responses in 3.5 min)</td>
<td></td>
<td>No</td>
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</tr>
</tbody>
</table>

n: number of participants in study; BF: breakfast consumption; NBF: breakfast omission; CPT: continuous performance test; MFFT: matching familiar figures test; WM: working memory
the acute, rather than the chronic, effects of the government breakfast programme. The findings indicated that there were no differences between those who consumed the standard government breakfast, compared to those who received the very low calorie breakfast, in measures of working memory, attention and problem solving. However, due to the cross-sectional nature of the study potential confounding variables could have influenced study outcomes, there was a relatively small number of participants (n = 34) and only the accuracy of working memory and attention were assessed, whilst speed was not considered.

More recently, the effects of breakfast consumption on cognitive function in adolescents have been examined using a cross-over study design (Widenhorn Müller et al, 2008). Whilst breakfast consumption enhanced the accuracy of visuospatial memory, there was no effect of breakfast on the accuracy of verbal memory or attention (Widenhorn Müller et al, 2008). Therefore, whilst the study shows some beneficial effects of breakfast consumption, some components of cognitive function were unaffected. This could be due to the cognitive measures being made immediately post-breakfast, with the beneficial effects of breakfast consumption not becoming apparent until later in the morning, as suggested by Hoyland et al (2009). Furthermore, only the accuracy of verbal memory, visuospatial memory and attention were assessed, with no measures made of the speed of responses, and therefore it is not possible to tell whether there were beneficial effects of breakfast on the speed of responses. Furthermore, the possibility of a speed-accuracy trade-off was not examined (i.e. was the improvement in the accuracy of visuospatial memory to the detriment of response times?).

Overall, from reviewing the studies in table 2.2, it appears the effects of breakfast consumption on cognitive function in adolescents are not clear. There is some evidence that breakfast may be beneficial, whereas a majority of studies show no effects of breakfast on
cognitive function in adolescents. It could be that breakfast consumption has less beneficial effects in adolescents compared to children, perhaps due to the differences between these populations (see section 2.1.2), or it could be that the research design, selection and timing of the cognitive tests and/or the nature of the breakfasts provided, did not allow for the beneficial effects of breakfast to be elucidated. Therefore, it is clear that further work needs to be conducted examining the effects of breakfast consumption on cognitive function in adolescents. This is a view echoed by the review of Hoyland et al (2009), indicating the need for future work in adolescents which uses counter-balanced repeated measure designs with large samples and assesses a range of cognitive functions, especially later in the morning, where the effects of breakfast may be more pronounced.

2.3: The Effects of Breakfast Composition on Cognitive Function

2.3.1: Adults

The studies which have examined the effects of breakfast composition on cognitive function in adult populations have predominantly focused on the glycaemic load (GL) of breakfast as their main independent variable. However, due to the related nature of GL and glycaemic index (GI) (see section 2.1.4) the breakfasts which are high GL are usually high GI, whilst low GL breakfasts are usually low GI (by definition, this will be true if the breakfasts have matched carbohydrate content). Of the studies which have been conducted in adults, two have been conducted in elderly subjects (Kaplan et al, 2000; Papanikolaou et al, 2006), whilst three studies have been conducted in healthy young adults (Benton et al, 2003; Benton & Nabb, 2004; Nabb & Benton, 2006).
Whilst one study with elderly participants showed no effects of the GL of breakfast on cognitive function (Kaplan et al, 2000), the other study found that performance on three tests of memory (digit span, word recall and paragraph recall) was enhanced following a low GL breakfast, when compared to following the high GL breakfast (Papanikolaou et al, 2006). However, the findings must be interpreted cautiously as the participants in the Papanikolaou et al (2006) study were patients with non-insulin dependent diabetes mellitus (NIDDM), thus the applicability of findings to healthy adults is not known. Furthermore, the study recruited a relatively small number of participants (n = 21), compared to other studies in the area.

The findings in healthy young adults generally support the findings with elderly subjects, in that a low GL (and low GI) breakfast is beneficial for cognitive function. For example, a breakfast high in slowly available glucose (SAG, i.e. a low GI breakfast) was beneficial for performance on memory tests later in the morning, compared to following consumption of a breakfast high in readily available glucose (RAG, i.e. a high GI breakfast) (Benton et al, 2003). Furthermore, a breakfast high in SAG (low GI) enhanced performance on a word recall test (used to assess memory) in comparison to a breakfast high in RAG (high GI), with a fasting condition in an intermediate position (i.e. the fasting condition produced better recall than the high RAG breakfast) (Benton & Nabb, 2004). A further study has also shown that participants’ performance following a low GL breakfast was enhanced on a test of memory, but was worse on a test of attention (Nabb & Benton, 2006). However, a number of factors are believed to mediate the effects of the GL/GI of breakfast on cognitive function in adults, including previous alcohol intake (Benton & Nabb, 2004) and glucose tolerance (Nabb & Benton, 2006).

Overall, the evidence suggests that a breakfast which slowly releases glucose into the bloodstream (i.e. a breakfast which is low GL, low GI and/or high in SAG) is beneficial for
cognitive function in adults. However, there are a number of factors which may mediate this relationship and thus, when reviewing the area, Gilsenan et al (2009) concluded that there was insufficient evidence to support a consistent effect of GL on cognitive performance and that further research was warranted.

2.3.2: Children

The studies which have considered the effects of breakfast composition on cognitive function in children (< 11 years old) are reviewed in table 2.3. Upon examination of table 2.3, it can be seen that of the four studies have been conducted in this area; two have breakfast GI as their main independent variable (Mahoney et al, 2005; Ingwersen et al, 2007), one examines breakfast GL (Benton et al, 2007), whilst the final study considers the effects of the energy content of breakfast (Benton & Jarvis, 2007). A major limitation of some of the studies in this area is the lack of nutritional information provided and thus the determination of the energy content, macronutrient content, GI and GL of the breakfasts provided was sometimes not possible, limiting the conclusions that could be drawn from such work.

Similar to the findings in adults (reviewed above), the evidence from studies in children suggests that a breakfast which slowly releases glucose into the bloodstream (i.e. low GI and/or GL), is beneficial for cognitive function, when compared to a high GI breakfast (Ingwersen et al, 2007), both a high GI breakfast and breakfast omission (Mahoney et al, 2005) and a high GL breakfast (Benton et al, 2007).

The study of Mahoney et al (2005) recruited 30 6-8 year olds and 30 9-11 year olds, who consumed a high GI breakfast, a low GI breakfast or omitted breakfast, and completed a battery of cognitive tests 60 min later. Of the components of cognitive function assessed
Table 2.3: A review of the studies examining the effects of breakfast composition on cognitive function in children

<table>
<thead>
<tr>
<th>Study Details</th>
<th>Methodology</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors</td>
<td>Conditions</td>
<td>Tests</td>
</tr>
<tr>
<td>Mahoney et al (2005)</td>
<td>High GI BF, low GI BF &amp; NBF</td>
<td>Map Task</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Digit Span</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Story Recall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPT (target = rhyming words)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rey complex figure copy &amp; recall test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Map Task</td>
</tr>
<tr>
<td></td>
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<td>Digit Span</td>
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<tr>
<td></td>
<td></td>
<td>Story Recall</td>
</tr>
<tr>
<td>Study Details</td>
<td>Methodology</td>
<td>Findings</td>
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<tr>
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</tr>
<tr>
<td><strong>Authors</strong></td>
<td><strong>Conditions</strong></td>
<td><strong>Tests</strong></td>
</tr>
<tr>
<td>&amp; <strong>Age of Participants</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mahoney et al (2005)</strong></td>
<td></td>
<td>CPT (target 'X' then 'B')</td>
</tr>
<tr>
<td>cont.</td>
<td></td>
<td>CPT (target = rhyming words)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rey complex figure copy &amp; recall test</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Benton et al (2007)</strong></td>
<td>High, medium &amp; low GL BF</td>
<td>Recall of objects test</td>
</tr>
<tr>
<td></td>
<td>Shakow paradigm</td>
<td>Sustained attention (lapses assessed by trial with RT &gt; 1000 ms)</td>
</tr>
<tr>
<td></td>
<td>Observation of classroom behaviour</td>
<td>Time on task</td>
</tr>
<tr>
<td><strong>Ingwerson et al (2007)</strong></td>
<td>High &amp; low GI BF</td>
<td>CDR Computer System</td>
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<tr>
<td>Study Details</td>
<td>Methodology</td>
<td>Findings</td>
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</tr>
<tr>
<td><strong>Authors</strong></td>
<td><strong>Conditions</strong></td>
<td><strong>Tests</strong></td>
</tr>
<tr>
<td><em>Ingwersen et al (2007) cont.</em></td>
<td>Habitual BF, classified as low (&lt;150 kcal), medium (150-230 kcal) or high (&gt;230 kcal) energy</td>
<td>Digit vigilance task</td>
</tr>
<tr>
<td>Benton &amp; Jarvis (2007)</td>
<td>Observation of classroom behaviour</td>
<td>Accuracy of attention</td>
</tr>
</tbody>
</table>

GI: glycaemic index; BF: breakfast; GL: glycaemic load; CPT: continuous performance test; CDR: cognitive drug research testing battery; WM: working memory
several showed consistent beneficial benefits of a low GI breakfast over a high GI breakfast and/or breakfast omission in both 6-8 and 9-11 year olds (spatial memory, working memory, auditory attention and visual perception) (Mahoney et al, 2005). Similarly, several components of cognitive function showed consistent null effects between the breakfast conditions (verbal memory & visual attention) (Mahoney et al, 2005). The consistency of the findings between the two age groups suggests that a low GI breakfast is beneficial for some components of cognitive function. In addition, the consistency of the null effects could have been due to a ‘real’ effect and several components of cognitive function were unaffected by the GI of breakfast, or it could be that the tests used to assess verbal memory and visual attention were not sensitive enough to show the effects of breakfast GI, and/or were not suitable for use in the study population.

Interestingly, within each age group (6-8 and 9-11 year olds), there were some effects of the GI of breakfast which were different between the boys and the girls. Specifically, in 6-8 year olds; the improved accuracy of working memory following a low GI breakfast was only evident in girls, whilst the accuracy of visual perception in boys was enhanced following a high GI breakfast compared to breakfast omission, whereas in girls this effect was reversed. Furthermore, similar to the findings in 6-8 year olds, in 9-11 year olds the improved accuracy of working memory following a low GI breakfast was only evident in girls (Mahoney et al, 2005). These findings are interesting in that they suggest a sex difference in the responses of the children.

However, regardless of the sex differences, overall these findings suggest that a low GI breakfast was the most beneficial for cognitive function in both 6-8 and 9-11 year olds. This is a finding echoed by the study of Ingwersen et al (2007), who found that the accuracy of both secondary memory and attention were enhanced following a low GI breakfast, when
compared to following a high GI breakfast. Similar to the findings regarding the GI of breakfast, a low GL breakfast has also been shown to be beneficial for cognitive function in children (Benton et al, 2007). Specifically, a lower GL breakfast predicted better performance on a test of working memory and fewer lapses in attention. Furthermore, using the more subjective measure of classroom behaviour, it was reported that participants spent more time on task in class and displayed fewer signs of frustrations when playing a computer game following a low GL breakfast, compared to following a high or medium GL breakfast (Benton et al, 2007).

In addition to the work examining the effects of the GI and GL of breakfast, Benton & Jarvis (2007) have also examined the effects of the energy content of breakfast on cognitive function in children. The findings indicate that participants displayed greater attention following a higher energy (> 150 kcal) compared to following a lower energy (< 150 kcal) breakfast (Benton & Jarvis, 2007). However, the study did not employ an objective test of attention, rather it utilised a more subjective measure, using classroom observation of the children during morning lessons. Furthermore, it appears that breakfast does need to be of a certain energy content to be beneficial for cognitive function, as the adverse effects of a lower energy breakfast were reversed by the consumption of a mid-morning snack, suggesting the additional energy intake is effective in removing the negative effects of a lower energy intake at breakfast (Benton & Jarvis, 2007).

Overall, the studies summarised in table 2.3 and reviewed above suggest that a low GI and/or a low GL breakfast are beneficial for cognitive function in children. This is also the conclusion of a recent review of the literature in the area, concluding that low GI and low GL breakfasts are beneficial for cognitive performance in children (Hoyland et al, 2009). Furthermore, the findings of the only study to date conducted examining the energy content
of breakfast suggest that breakfasts with higher energy content are the most beneficial for cognitive function, whereas a lower energy breakfast does not confer the same benefits.

2.3.3: Adolescents

Similar to the focus of the literature in adults and children, the primary variable(s) of interest when examining breakfast composition and cognitive function in adolescents has been GI and/or GL. As with children, there has also been one study examining the effects of the energy content of breakfast. Of the four studies to examine GI/GL, there are three published papers (Wesnes et al, 2003; Smith & Foster, 2008; Micha et al, 2010) and one published abstract (Micha et al, 2008), which are summarised in table 2.4. From these four studies, twelve cognitive tests have been examined and interestingly, the evidence regarding the effects of breakfast GI on cognition is equivocal. Six of the twelve tests (50%) show that a low GI breakfast is most beneficial for cognitive function, four (33%) show a high GI breakfast is most beneficial, whilst two (17%) show no differences between the high and low GI breakfast conditions. Therefore, just from this brief overview it is clear that the effects of the GI of breakfast on adolescents’ cognitive function are more equivocal than the effects in children and adults, where a low GI breakfast appears to be most beneficial.

Findings in line with those in children and adults suggesting that a low GI breakfast is the most beneficial for cognitive function were found in the study of Wesnes et al (2003). Specifically, the speed and accuracy of working memory and secondary memory were greater following a low GI breakfast when compared to following both a high GI breakfast and breakfast omission (Wesnes et al, 2003). These effects were particularly evident at the later morning testing sessions (240 min post breakfast), where significant declines in performance
### Table 2.4: A review of the studies examining the effects of breakfast composition on cognitive function in adolescents

<table>
<thead>
<tr>
<th>Authors</th>
<th>n</th>
<th>Age of Participants</th>
<th>Conditions</th>
<th>Tests</th>
<th>Methodology</th>
<th>Variables Assessed</th>
<th>Timing of Tests</th>
<th>Effect?</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wesnes et al (2003)</td>
<td>29</td>
<td>9-16</td>
<td>2 cereal BF (low GI), glucose drink (high GI) and NBF</td>
<td>CDR computer system</td>
<td>Speed of WM</td>
<td>Pre &amp; 60, 120, 180 &amp; 240 min post BF</td>
<td>Yes</td>
<td>Greater improvement following low GI BF vs. high GI BF &amp; NBF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracy of WM</td>
<td></td>
<td></td>
<td></td>
<td>Accuracy better maintained following low GI BF vs. high GI BF &amp; NBF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed of secondary memory</td>
<td></td>
<td></td>
<td></td>
<td>Greatest improvement following low GI BF vs. high GI BF &amp; NBF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracy of attention</td>
<td></td>
<td></td>
<td></td>
<td>Accuracy greater following low GI BF vs. high GI BF</td>
</tr>
<tr>
<td>Micha et al (2008)</td>
<td>74</td>
<td>11-14</td>
<td>Allocated to high/low GL groups, within which high and low GI BF were provided</td>
<td>Stroop test</td>
<td>Speed of attention</td>
<td>Pre &amp; post BF (exact timings not stated)</td>
<td>Yes</td>
<td>Quicker following high GI BF vs. low GI BF</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed of information processing task</td>
<td>Number of correct responses in 3 min (i.e. both speed and accuracy of attention)</td>
<td>Verbal fluency</td>
<td></td>
<td></td>
<td>High GI BF vs. low GI BF produced better performance</td>
</tr>
<tr>
<td>Smith &amp; Foster (2008)</td>
<td>38</td>
<td>14-17</td>
<td>High or low GI BF</td>
<td>Modified California Verbal Learning Test</td>
<td>Accuracy of verbal episodic memory</td>
<td>20, 60 and 100 min post BF</td>
<td>Yes</td>
<td>High GI BF produced greater accuracy at 100 min post BF vs. low GI BF (no effects at 20 or 60 min post BF)</td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>n</td>
<td>Age of Participants</td>
<td>Conditions</td>
<td>Tests</td>
<td>Variables Assessed</td>
<td>Timing of Tests</td>
<td>Effect?</td>
<td>Findings</td>
<td>Direction</td>
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<tr>
<td>Micha et al (2010)</td>
<td>60</td>
<td>11-14</td>
<td>Self-selected BF classified into high or low GI &amp; high or low GL</td>
<td>Immediate word recall Stroop test</td>
<td>Accuracy of WM</td>
<td>90-120 min post BF</td>
<td>Yes</td>
<td>High GI BF produced greater accuracy vs. low GI BF</td>
<td>---</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed of selective attention</td>
<td>Speed of selective attention</td>
<td></td>
<td>No</td>
<td>---</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed and accuracy of attention</td>
<td>Speed and accuracy of attention (number of correct responses in 3 min)</td>
<td></td>
<td>Yes</td>
<td>Low GI &amp; high GL BF associated with better performance</td>
<td>---</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Word generation task</td>
<td>Verbal fluency</td>
<td></td>
<td>No</td>
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<td>---</td>
</tr>
<tr>
<td>Michaud et al (1991)</td>
<td>319</td>
<td>13-20</td>
<td>Usual energy BF (389 kcal) &amp; higher energy BF (634 kcal)</td>
<td>Scale test</td>
<td>Accuracy of WM</td>
<td>180 min post BF</td>
<td>Yes</td>
<td>Higher energy BF enhanced accuracy vs. usual energy BF</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Concentration 'word' test</td>
<td>Speed and accuracy of attention (number of correct responses in 6 min)</td>
<td></td>
<td>Yes</td>
<td>Usual energy BF enhanced performance vs. higher energy BF</td>
<td>---</td>
</tr>
</tbody>
</table>

n: number of participants in study; GI: glycaemic index; BF: breakfast; GL: glycaemic load; CPT: continuous performance test; CDR: cognitive drug research testing battery; WM: working memory
were seen following the high GI breakfast and breakfast omission, whereas performance was better maintained following the low GI breakfast cereals (Wesnes et al, 2003). However, the findings must be interpreted cautiously for two main reasons: firstly, the wide age range of participants (9-16 year olds) means there were significant age and maturity differences, making conclusions specific to adolescents difficult to make; and secondly, the study used a glucose drink to simulate a high GI breakfast, rather than providing high GI breakfast foods and thus the everyday applicability of the findings was limited.

Perhaps in an attempt to overcome the shortcomings of the above study, Smith & Foster (2008) examined the effects of a high and a low GI breakfast (both using ‘everyday’ breakfast foods) on adolescents’ verbal episodic memory across the morning. In contrast to the above findings, the findings indicate that the high GI breakfast was the most beneficial for the accuracy of verbal episodic memory, when compared to the low GI breakfast (Smith & Foster, 2008). Interestingly, despite the contrasting direction of the findings, the differences between the breakfasts were only evident later in the morning (100 min post breakfast), whilst performance 20 and 60 min post breakfast was not different between the trials, similar to the findings of Wesnes et al (2003). The authors suggested that the high GI breakfast was most beneficial in this study due to the higher blood glucose concentrations (following the high GI breakfast when compared to the low GI breakfast), which would be beneficial under the conditions of divided attention (i.e. when the cognitive task is more difficult). However, this observation is curious given that there were no significant differences in blood glucose concentrations following the high and low GI breakfasts.

Two further studies examined the combined effects of the GI and GL of breakfast on cognitive function in adolescents (Micha et al, 2008; Micha et al, 2010). In the first study, participants were allocated to a high or low GL group, within which high and low GI
breakfasts were provided (Micha et al, 2008). Whilst exact details on the timing of the cognitive tests were not provided, there were equivocal effects. Specifically, the speed of attention and information processing was greater following a high GI breakfast, whereas verbal fluency was greater following a low GI breakfast (Micha et al, 2008). Furthermore, when adolescents were asked to self-report their breakfast, which was subsequently analysed and classified according to GI and GL, whilst a high GI breakfast was beneficial for the accuracy of working memory, a low GI and high GL breakfast was beneficial for the speed of information processing (Micha et al, 2010). However, an obvious limitation of this study is the use of self-report and subsequent analysis to classify the breakfasts according to GI and GL, plus due to the cross-sectional nature of the study, a number of confounding variables could have affected the study outcomes.

As with children, in addition to the work examining the effects of the GI and GL of breakfast, the effects of the energy content of breakfast on adolescents’ cognitive function have also been examined (Michaud et al, 1991). Participants were asked to consume their usual breakfast on their first trial, then ‘eat more’ for their subsequent trial 14 days later, with a caveat being that 35% of participants failed to achieve this. Data for these participants was reversed, with their ‘higher energy’ trial being first, then their ‘usual energy’ trial 14 days later. Whilst the accuracy of working memory was enhanced following a higher energy breakfast, attention was enhanced following the lower energy breakfast (Michaud et al, 1991). However, it must also be considered that because the trials were not completed in a counterbalanced order, learning effects could have influenced performance on the subsequent (higher energy intake) trial.

Overall, the evidence from studies examining the effects of breakfast composition (GI, GL and energy content) on cognitive function in adolescents is equivocal (summarised in
It has been shown that whilst a low GI breakfast is beneficial for some components of cognitive function in some studies, a high GI breakfast has also been shown to be beneficial in other studies. Furthermore, the effects of the energy content of breakfast on adolescents’ cognitive function also appear to be equivocal, with the only study examining this to date showing mixed effects of higher energy intake at breakfast. Therefore, the effects of breakfast composition clearly warrant further research, to allow future recommendations regarding the optimum composition and size of breakfast for cognitive function in adolescent populations (Hoyland et al, 2009).

2.4: Nutritional Mechanisms

In addition to documenting the effects of breakfast consumption and composition on cognitive function in young people, some studies have attempted to provide potential mechanisms to explain the effects. For example, it has been suggested that by alleviating hunger, breakfast consumption enhances mood and, subsequently, cognitive function in children (Pollitt et al, 1978) and adolescents (Widenhorn-Müller et al, 2008). A further proposed mechanism is enhanced nutritional status associated with regular breakfast consumption, which may, in turn, improve cognitive function (Pollitt & Matthews, 1998). However, this chronic change in nutritional status is unlikely to explain the short-term, acute effects of breakfast consumption on cognitive function as reviewed above. It is possible, however, that in longer-term studies in young people with poor baseline nutritional status (as reviewed by Grantham McGregor, 2005), an improvement in nutritional status may contribute to enhanced cognitive function (Pollitt & Matthews, 1998).

More recently, it has been suggested that breakfast consumption modifies the metabolic responses to fasting and maintains a supply of nutrients to the central nervous

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system (Rampersaud et al, 2005). Glucose has been frequently suggested as a key nutritional mediator for cognitive function. This is unsurprising given that it is the only fuel that can be used by the brain directly. The leading role of glucose is well supported in adults, where glucose provision has been related to improved performance on the Stroop test (Dye et al, 2000) and enhanced memory (Benton & Sargent, 1992).

In their review of early studies showing enhanced cognitive function following breakfast consumption in young people, Pollitt et al (1998) suggest that such effects may be mediated by changes in glucose regulation. However, as previously discussed, most studies in young people have not measured, or at least have not included serial measurements of blood glucose following their dietary interventions. Of the few studies that have measured blood glucose, some suggest it plays a leading role (e.g. Smith & Foster, 2008), whereas others have shown glucose is not a key determinant of cognitive performance (e.g. Cromer et al., 1990; Michaud et al., 1991).

Interestingly, studies examining the effects of the GI and GL of breakfast provide further insight into the potential mechanisms that may be at work. For example, Micha et al (2008) found that whilst a high GI breakfast (and the associated higher blood glucose concentrations) is beneficial for adolescents’ performance on the Stroop test, a low GI breakfast (and the associated lower blood glucose concentrations) is beneficial for adolescents’ performance on a word generation task. This suggests that either blood glucose concentration (within the normal postprandial range, i.e. after high and low GI breakfasts) is not a key determinant of cognitive function and other mechanisms may be responsible, or that higher glucose concentrations are beneficial for some components of cognitive function, whereas they are detrimental for other components. However, given that the glycaemic responses were not measured in the study of Micha et al (2008), such mechanisms can only be speculated upon.
From this review it can be seen that there is ambiguity in the literature regarding the effect of glucose on cognitive function in young people. Furthermore, no studies examining cognitive function in young people to date have measured insulin concentrations following their dietary interventions. Given the central role of insulin for glucose regulation and cognitive function (Laron, 2009), the simultaneous measurement of plasma insulin and glucose concentrations would allow us to further our understanding of the mechanisms responsible for nutritionally induced changes in cognitive function in young people.

2.5: Recommendations for Future Research Concerning Nutritional Interventions and Cognitive Function

From reviewing the literature to date, the following recommendations for future research assessing the effects of breakfast consumption and composition on cognitive function in young people can be made:

- Where possible, studies should employ a counter-balanced cross-over study design, to eliminate the role of confounding variables in influencing study outcomes. However, where cross-sectional design is required, potential confounding variables must be carefully controlled for.

- Studies should focus on specific populations, especially with regards to age and the distinction between children and adolescents. Another factor to consider, especially when working in under nourished populations, is the basal nutritional status of the participants.

- A range of pre-validated cognitive function tests should be selected, which examine specific cognitive functions and are suitable for the study population. Where possible,
studies should also employ a battery of tests assessing multiple components of cognitive function, allowing the greatest claims to be made regarding the effects on overall cognitive function. An opportunity for participants to familiarise themselves with the tests should be provided and where possible, computer based tests assessing speed and accuracy should be used. These tests should be conducted across the school morning, with an awareness that the effects of breakfast consumption and composition are likely to be more apparent later in the morning (at least 120 min following breakfast).

- Given their well documented effects on cognitive function, diet and exercise (see section 2.6) should be controlled on the day of the trial. Furthermore, given that the evening meal the night before has been shown to affect glycaemic and insulinaemic responses the following day (Wolever et al, 1988), and the well documented effects of glucose and insulin on cognitive function (Dye et al, 2000; Laron, 2009), the evening meal should be repeated for subsequent trials.

- The breakfasts provided must be clearly explained and be as close to habitual breakfast consumption as possible. When examining breakfast composition, the breakfasts provided should be matched on all key variables except the variable of interest. Furthermore, where possible within the ethical constraints of working with young people, the glycaemic and insulinaemic responses to the meals of differing GI and GL should be reported, potentially allowing an insight into the mechanisms mediating any nutritionally induced effects on cognitive function.
2.6: The Acute Effects of Exercise on Cognitive Function

2.6.1: Adults

The effects of an acute bout of exercise on cognitive function in adults have been widely studied during the 20th century, leading to several authors conducting reviews of the available evidence (Etnier et al, 1997; Brisswalter et al, 2002; Tomporowski, 2003). In their review, Brisswalter et al (2002) focused on the effects of exercise on cognitive function during the exercise itself, concluding that there was clear support for an enhanced cognitive performance during exercise. However, it was also noted that these effects were seen mainly with complex decisional tasks and with exercise of greater than 20 min duration and of a moderate to high intensity (40-80% maximal oxygen uptake) (Brisswalter et al, 2002).

Other studies have examined the chronic, long term, effects of exercise training and the acute effects of an exercise bout on subsequent cognitive function (i.e. after the exercise has finished) (Etnier et al, 1997). The meta-analysis included the findings of 134 studies which allowed the calculation of an effect size (ES), with the findings indicating an overall ES of 0.25, indicative of a small, positive effect of exercise on cognitive function (Etnier et al, 1997). Interestingly, there were both chronic and acute effects of exercise on adults’ cognitive function and the conclusion drawn from the meta-analysis was that there was a need for well controlled, true experimental studies, to examine the area further (Etnier et al, 1997).

Subsequently, a review focussing on the acute effects of a bout of exercise on cognitive function was completed by Tomporowski (2003). The findings of this review indicate that exercise has an acute beneficial effect on cognitive function and can influence both the speed and accuracy of responses. Furthermore, it is suggested that tasks which
require a greater degree of decision making may be particularly affected, especially by exercise which is of a moderate intensity and duration (approximately 40-80% maximal oxygen uptake and 15-60 min in duration) (Tomporowski, 2003), in line with the inverted U hypothesis proposed by Easterbrook (1959). However, the review highlighted the need for further research in two main areas; to determine the time course of the effects of an acute bout of exercise (e.g. during, immediately after, 60 min after exercise etc.), and to examine the effects of an acute bout of exercise on cognitive function in young people.

Therefore, overall the evidence in adults suggests that an acute bout of exercise does enhance cognitive function, but this effect is dependent on a range of factors, including: the intensity and duration of exercise, the cognitive tests used, and the timing of the cognitive tests relative to the exercise. The subsequent section will review the evidence available in young people, considering children and adolescents separately, consistent with the previous sections of this review.

2.6.2: Children

Data from the aforementioned meta-analysis included studies conducted in children, with the results in elementary school children (6-13 years old) showing a small but positive relationship between exercise and cognitive function (ES = 0.36) (Etnier et al, 1997). These findings are similar to those reported for adult populations, but the meta-analysis included studies examining both the acute and chronic effects of exercise, published and unpublished studies, and provided no details of the individual studies (e.g. mode, intensity and duration of exercise, participant characteristics, and the tests of cognitive function used); thus generalisations must be made cautiously.
The focus of the subsequent section of this review is to examine the evidence regarding the acute effects of exercise on cognitive function in children, with a search of the literature yielding five published studies examining this area which are reviewed in table 2.5 (Gabbard & Barton, 1979; Caterino & Polak, 1999; Hillman et al, 2009; Ellemberg & St-Louis-Descênes, 2010; Hill et al, 2010). Much of the early research in this area focussed around justifying the presence of physical education (PE) classes in the curriculum and examining whether or not PE was detrimental to academic achievement in school children (Kirkendall, 1985). Indeed, a review in this area concluded that daily physical activity could be introduced in primary schools (i.e. in children 5-11 years old) without compromising academic achievement (Shephard, 1997).

Two of the early studies reviewed in table 2.5 have examined the effects of a PE lesson on cognitive function in children, primarily to address whether or not participation in a PE class could affect cognitive function, and as a result, academic achievement (see section 2.1.3) (Gabbard & Barton, 1979; Caterino & Polak, 1999). The findings generally show a positive effect of exercise on cognitive function, with mathematical computation enhanced in 7-8 year olds 50 min into a PE lesson when compared to a pre-lesson baseline level (Gabbard & Barton, 1979), and attention enhanced following a PE lesson compared to following normal classroom activities in 9-10 year olds (Caterino & Polak, 1999). Interestingly, in the latter study, there was no effect of the PE lesson on 7-8 or 8-9 year olds, but these null findings could be due to either the exercise completed during the PE lesson not being strenuous enough to elicit effects in these age groups (15 min stretching and walking), or the Woodcock Johnson test of concentration not being suitable for the younger children (Caterino & Polak, 1999).
Table 2.5: A review of the studies examining the acute effects of a bout of exercise on cognitive function in children

<table>
<thead>
<tr>
<th>Authors</th>
<th>n</th>
<th>Age of Participants</th>
<th>Conditions</th>
<th>Tests</th>
<th>Variables Assessed</th>
<th>Timing of Tests</th>
<th>Effect?</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabbard &amp; Barton (1979)</td>
<td>106</td>
<td>7-8</td>
<td>PE lesson</td>
<td>Mathematical computation test</td>
<td>Speed and accuracy of mathematical computation (number of correct responses in 2 min)</td>
<td>Pre, during (20, 30, 40 &amp; 50 min) &amp; post PE lesson</td>
<td>Yes</td>
<td>Enhanced accuracy at 50 min vs. all other time points</td>
</tr>
<tr>
<td>Caterino &amp; Polak (1999)</td>
<td>54</td>
<td>7-8</td>
<td>PE lesson (15 min stretching &amp; walking) or classroom activities</td>
<td>Woodcock-Johnson Test of Concentration</td>
<td>Speed and accuracy of attention (number of correct responses in 3 min)</td>
<td>Immediately following PE lesson or classroom activities</td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>71</td>
<td>8-9</td>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>52</td>
<td>9-10</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
<td>Higher scores following PE lesson vs. classroom activities</td>
<td></td>
</tr>
<tr>
<td>Hillman et al (2009)</td>
<td>20</td>
<td>9-10</td>
<td>20 min running at 60% maximum heart rate (exercise trial) &amp; resting trial</td>
<td>Modified Flanker task</td>
<td>Speed of attention Accuracy of attention</td>
<td>Post-exercise</td>
<td>No</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Yes</td>
<td>Greater accuracy on incongruent (more complex) level following exercise vs. resting trial</td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>n</td>
<td>Age of Participants</td>
<td>Conditions</td>
<td>Tests</td>
<td>Variables Assessed</td>
<td>Timing of Tests</td>
<td>Effect?</td>
<td>Findings</td>
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<tr>
<td>Elleemberg &amp; St-</td>
<td>72</td>
<td>7-10</td>
<td>30 min cycling at heart rate of 130 beats.min(^{-1}) (exercise group) or</td>
<td>Tests created in Matlab(^{TM})</td>
<td>Simple RT</td>
<td>Pre- &amp; post-exercise (exact timing unknown)</td>
<td>Yes</td>
<td>Exercise group quicker later in the morning</td>
</tr>
<tr>
<td>Louis-Louis-</td>
<td></td>
<td></td>
<td>rest (resting group)</td>
<td></td>
<td>Choice RT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Descènes (2010)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracy on choice RT task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hill et al</td>
<td>1224</td>
<td>8-11</td>
<td>15 min PE post-lunch (exercise trial) &amp; resting trial</td>
<td>5 psychometric tests (one per day for a week)</td>
<td>Results collapsed across tests to provide mean score</td>
<td>At the end of the school day (~1 h post-exercise)</td>
<td>Yes</td>
<td>Enhanced performance at end of the school day following PE vs. resting trial</td>
</tr>
</tbody>
</table>

n: number of participants in study; PE: physical education; bpm: beats per minute; RT: reaction time
More recently, using more sensitive computer-based tests of cognitive function, both the speed and accuracy of attention were assessed following 20 min treadmill running at 60% of maximum heart rate, compared to following 20 min of rest (Hillman et al, 2009). Whilst the speed of responses was unaffected, participants achieved more correct responses on the incongruent (more complex) stimuli on the Flanker task following exercise, when compared with continuing to rest (Hillman et al, 2009). Furthermore, both simple and choice response times were enhanced in a group of 7-10 year olds who had completed 30 min cycling at a heart rate of 130 beats.min\(^{-1}\) (similar to the 60% maximum heart rate used in the Hillman et al (2009) study) when compared with a control group who continued to rest (Ellemberg & St-Louis-Deschênes, 2010). However, the accuracy of responses on the choice response time task was not different between the exercise and control groups (Ellemberg & St-Louis-Deschênes, 2010).

Interestingly, when comparing the findings of the two above studies, in the study of Hillman et al (2009) the accuracy of responses was enhanced following exercise whilst speed was unaffected, whereas in the study of (Ellemberg & St-Louis-Deschênes, 2010) these effects were reversed, with the speed of responses improved and accuracy unaffected by exercise. However, Ellemberg & St-Louis-Deschênes (2010) did not employ a cross-over study design, and only compared children who had and had not completed the exercise using a cross-sectional study design, introducing the possibility that confounding variables could affect the study outcomes. Furthermore, whilst the study of Hillman et al (2009) assessed attention using a modified Flanker task, Ellemberg & St-Louis-Deschênes (2010) assessed simple and choice response times on tests created for the purpose of the study. Thus the variation in findings could be due to the different components of cognitive function being measured and the different tests used.
In the largest scale study to date examining the acute effects of exercise on children’s cognitive function, Hill et al (2010) tested 1224 children (8-11 years old), who completed 15 min PE following lunch, or continued to rest, then completed one of five cognitive function tests (one per day for a week) at the end of the school day (approximately 60 min post exercise). An overall score for cognitive function was attained by averaging performance across the five tests, with the findings suggesting a beneficial effect of the exercise, when compared to the resting trial (Hill et al, 2010). However, a caveat to these findings is that the beneficial effect of exercise was only seen when the exercise trials were completed during the second week, where learning effects may have been a contributory factor, although the authors refute this (Hill et al, 2010).

In conclusion, despite the limited number of studies conducted in this area (table 2.5), the evidence suggests that overall exercise does have a beneficial effect of children’s cognitive function. This is in line with the findings of a meta-analysis which yielded an overall ES of 0.32, suggesting that there is a significant positive relationship between physical activity and cognitive function in children (Sibley & Etnier, 2003). The authors also stated that there was a consistency in the literature, with 10 of the 15 studies (mostly unpublished and thus not included in this review) showing positive effects and furthermore, when including only the studies examining the acute effects of exercise, the ES was increased slightly to 0.37 (Sibley & Etnier, 2003). However, similar to the weaknesses of the earlier meta-analysis (Etnier et al, 1997), the findings of both published and unpublished studies were included and details of the studies were not provided (e.g. on the mode, duration and intensity of exercise, the participant characteristics, and the tests of cognitive function used). Therefore, the ability to draw definitive conclusions from the meta-analysis is limited, and the need for further, well designed, research examining the acute effects of exercise and the
mechanisms for such an effect are required (Sibley & Etnier, 2003). However, overall the evidence suggests that, at the very least, time spent in PE classes will not impair children’s cognitive function or ultimately, academic achievement (Sibley & Etnier, 2003).

2.6.3: Adolescents

The meta-analysis of Etnier et al (1997) also included some data from adolescent populations. Whilst not examining ‘adolescents’ as a whole, the ES from 8 studies in ‘high school’ students (11-18 years old) was 0.77, indicating a large, positive effect of exercise on adolescents cognitive function (Etnier et al, 1997). However, once again the studies included in the meta-analysis were largely unpublished and no details of the individual studies were provided (Etnier et al, 1997).

Published studies which have examined the effects of exercise on cognitive function in adolescents are reviewed in table 2.6 (Raviv & Low, 1990; Zervas et al, 1991; McNaughten & Gabbard, 1993; Budde et al, 2008; Stroth et al, 2009; Travlos, 2010). Similar to the work in children, some of the early work was conducted using paper and pencil tests, with a focus on justifying the presence of PE in the curriculum. One study indicated there were no differences in attention after a PE lesson compared to following a science lesson (Raviv & Low, 1990). However, the study used a cross-sectional design, only comparing those children who had completed science and PE lessons and thus there was the potential for confounding variables (e.g. lesson preference) to influence the study outcomes.

One study to indicate a beneficial effect of exercise on adolescents’ cognitive function examined mathematical computation following a 20, 30 or 40 min bout of walking, compared to a resting (control) group (McNaughten & Gabbard, 1993). Following either 30 or 40 min
### Table 2.6: A review of the studies examining the acute effects of a bout of exercise on cognitive function in adolescents

<table>
<thead>
<tr>
<th>Authors</th>
<th>n</th>
<th>Age of Participants</th>
<th>Conditions</th>
<th>Tests</th>
<th>Variables Assessed</th>
<th>Timing of Tests</th>
<th>Effect?</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raviv &amp; Low (1990)</td>
<td>96</td>
<td>11-12</td>
<td>PE or science lesson</td>
<td>d2 Concentration test</td>
<td>Speed and accuracy of attention (number of correct responses in 5 min)</td>
<td>Beginning and end of lessons (exact timing unknown)</td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td>Zervas et al (1991)</td>
<td>18</td>
<td>11-14</td>
<td>20 min running at speed above 'anaerobic threshold'</td>
<td>Cognitrone Test</td>
<td>Speed of attention Accuracy of attention</td>
<td>Pre- &amp; immediately post-exercise</td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td>McNaughten &amp; Gabbard (1993)</td>
<td>120</td>
<td>11-12</td>
<td>20, 30 and 40 min walking (exercise groups) or resting (control) groups</td>
<td>Mathematical Computation Test</td>
<td>Speed and accuracy of mathematical computation (number of correct responses in 90 seconds)</td>
<td>Post-intervention (exact timing unknown)</td>
<td>Yes</td>
<td>Accuracy enhanced post-exercise vs. pre-exercise levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Enhanced performance later in the morning following 30 and 40 min exercise vs. 20 min exercise</td>
</tr>
<tr>
<td>Authors</td>
<td>n</td>
<td>Age of Participants</td>
<td>Conditions</td>
<td>Tests</td>
<td>Variables Assessed</td>
<td>Timing of Tests</td>
<td>Effect?</td>
<td>Findings</td>
</tr>
<tr>
<td>------------------</td>
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<td>-----------------------------------------------</td>
<td>---------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Budde et al</td>
<td>115</td>
<td>13-16</td>
<td>10 min coordinative exercises (CE) or a normal sports lesson (NSL)</td>
<td>d2 Concentration test</td>
<td>Speed of attention, Accuracy of attention, Errors in attention</td>
<td>Pre-intervention (week 1) and immediately post-intervention (week 2)</td>
<td>Yes</td>
<td>CE enhanced speed of responses vs. NSL CE enhanced accuracy of responses vs. NSL</td>
</tr>
<tr>
<td>Stroth et al</td>
<td>35</td>
<td>13-14</td>
<td>20 min cycling at 60% maximum heart rate (exercise trial) &amp; resting trial</td>
<td>Modified Flanker Task</td>
<td>Speed of attention, Accuracy of attention</td>
<td>Post-intervention (exact timing unknown)</td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td>Travlos</td>
<td>48</td>
<td>13-15</td>
<td>Intense PE class &amp; resting trials</td>
<td>Mathematical Computation Test</td>
<td>Speed and accuracy of mathematical computation (number of correct in 2 min)</td>
<td>10 min post-exercise (at 6 different times during the day)</td>
<td>Yes</td>
<td>Enhanced performance following exercise during the 1st, 3rd and 5th hours of the day vs. resting trial. Enhanced performance on resting trial vs. exercise trial during 6th hour of the day</td>
</tr>
</tbody>
</table>

n: number of participants in study; PE: physical education; CE: coordinative exercises; NSL: normal sports lesson
walking mathematical computation was better than following only 20 min of walking (McNaughten & Gabbard, 1993). These findings therefore suggest that exercise must be of a sufficient duration to influence cognitive function. However, this study assessed mathematical computation, a sum of a number of components of cognitive function (and mathematical intelligence), rather than focusing on a specific component of cognitive function. Furthermore, the exact timing of the mathematical computation test following the walking was not clear and thus the timescale of these effects is not known.

A number of studies conducted in adolescent populations have examined the effects of physical fitness, rather than exercise (and physical activity) on cognitive function. The full details of these studies are beyond the scope of this review and are reviewed by Tomporowski (2008). Of direct relevance here however are the studies where the acute effects of exercise were examined in addition to the (longer-term) effects of physical fitness (Zervas et al, 1991; Stroth et al, 2009). For example, in the study of Zervas et al (1991) whilst no effects of physical fitness were seen, there was a greater accuracy of attention following 20 min running (at an intensity above an individual’s ‘anaerobic threshold’), when compared to pre-exercise performance on the same test.

In contrast to these findings, in the study of Stroth et al (2009) there was no effect of 20 min cycling at 60 % maximum heart rate, when compared with continuing to rest, on either the speed or accuracy of attention on a modified Flanker task. However, when measuring event related potentials in the brain, adolescents with higher physical fitness showed enhanced preparation and more efficient executive control of attention when compared to adolescents with lower physical fitness (Stroth et al, 2009). Therefore, whilst the findings of Stroth et al (2009) show no acute effects of exercise on adolescents’ attention,
fitter individuals have more efficient control of attention, suggesting a long term beneficial effect of exercise, should the exercise lead to increased fitness levels.

In more recent work, the acute effects of exercise on adolescents’ cognitive function at different times during the school day were examined (Travlos, 2010). Specifically, participants completed an intense PE class (40 min interval running at a heart rate of approximately 175 beats.min\(^{-1}\)) and 2 resting (control) trials. Interestingly, the findings suggested that the acute effects of exercise were different at different times of the school day, as after the first, third and fifth periods mathematical computation was enhanced following exercise, whereas after the sixth period (at the end of the school day) mathematical computation was greater on the resting trials (Travlos, 2010). Therefore, these findings suggest that the timing of exercise during the school day is important, with exercise later in the day possibly leading to greater levels of fatigue and consequently, decrements in cognitive function (Travlos, 2010).

The effects of different types of exercise on adolescents’ cognitive function have also been examined. Specifically, Budde et al (2008) found bilateral coordinative exercise to be more beneficial than participation in a normal sports lesson for attention (Budde et al, 2008). The authors suggested that bilateral coordinated exercise activated certain areas of the brain (frontal lobe and cerebellum), and thus was particularly beneficial for cognitive function. However, the study was conducted in an elite performance school where participants were already completing 25-30 hours of exercise a week and thus the applicability of the findings to adolescents in ‘normal’ schools is unknown.

Overall, it appears that the effects of exercise on cognitive function in adolescents are equivocal and that further work is needed in this area. In four of the six studies examining the acute effects of exercise there was a beneficial effect on cognitive function, whereas two
studies showed no effects. However, comparisons between the studies are difficult to make due to differences in; study design, exercise mode, intensity and duration, and the components of cognitive function assessed. However, two meta-analyses indicate a positive effect of exercise on adolescents’ cognitive function (Etnier et al, 1997; Sibley & Etnier, 2003) and, at the least, suggest it is an area which warrants further research. It has also been suggested that future research should focus on specific components of cognitive function, which may provide the basis for future recommendations regarding the inclusion of PE classes in the curriculum to enhance adolescents’ cognitive function, and ultimately, academic achievement (Keeley & Fox, 2009).

2.7: Exercise Mechanisms

Where beneficial effects of exercise on cognitive function have been observed, a number of potential mechanisms have been postulated to mediate such effects. A majority of the work that has been conducted regarding potential mechanisms has been conducted in adults, with a limited number of studies also conducted in young people. This section of the review will examine the evidence supporting each of the postulated mechanisms, with direct relevance to the effects of exercise on cognitive function in young people.

One such mechanism which has been suggested to mediate the relationship between exercise and cognitive function is an increase in cerebral blood flow associated with exercise. Traditionally, it was believed that blood flow to the brain was steady during exercise, but recent evidence suggests exercise does indeed increase cerebral blood flow (for review see Querido & Sheel, 2007). Furthermore, it has been suggested that the increase in blood flow to the brain enhances the delivery of glucose and oxygen to neural tissues, whilst also enhancing
the clearance of waste products such as carbon dioxide, which in turn improves cognitive function (Jorgensen et al, 2000). However, these suggestions are based on findings in adults and to date, none of the studies reviewed in tables 2.5 and 2.6 have measured cerebral blood flow in young people either during or after exercise. Therefore, whilst an increase in cerebral blood flow during (and following) exercise is a possible mechanism for exercise induced improvements in cognitive function, current data in young people cannot confirm, or refute, this mechanism, as cerebral blood flow has not been measured, nor has its direct effect on cognitive function.

An intriguing potential mechanism mediating the effects of exercise on cognitive function is the use of lactate as an oxidative substrate for the brain (Schurr, 2006). However, this topic is poorly understood, with some evidence suggesting that lactate is only oxidised by the brain during hypoglycaemia (Maran et al, 1994), thus would not be oxidised by participants in the studies reviewed here (it is highly unlikely that any of the participants in such studies would be in a hypoglycaemic state). Nevertheless, the potential role of lactate within the brain is an area which warrants further research, including its role in mediating any exercise induced effects on cognitive function.

It has also been suggested, including in studies in young people (Stroth et al, 2009; Hillman et al, 2009), that changes in signalling within the brain may be responsible for exercise induced changes in cognitive function. Specifically, event related potentials have been examined during the modified Flanker task used by Hillman et al (2009). The results indicate that following exercise a greater P3 amplitude was observed in the incongruent trials following exercise, when compared with continuing to rest. Interestingly, participants also achieved more correct responses on the incongruent trials following the exercise (Hillman et
al, 2009), suggesting that the improvement in accuracy following exercise may be due to changes in signalling within the brain.

However, contrary to these findings, Stroth et al (2009) found no effects of exercise on P3 amplitudes. This could be due to the different components of cognitive function measured (compared with the study of Hillman et al (2009)), resulting in different areas of the brain being activated. However, whilst there were no acute effects of exercise on event related potentials, adolescents with higher levels of physical fitness showed greater CNV amplitudes (indicative of greater preparation) and decreased N2 amplitudes (indicative of more efficient executive control) (Stroth et al, 2009). However, as already mentioned in the above review, these effects did not affect performance on the cognitive function tests, and were associated with the chronic effects of increased physical fitness, rather than the acute effects of exercise, the focus of this section of the review.

It has also been suggested that certain types of exercise may increase pre-activation in certain areas of the brain (namely the frontal lobe and cerebellum during bilateral coordinative exercise, i.e. exercise which requires activation of these brain areas) and thus, improve subsequent cognitive function (Budde et al, 2008). However, activation of other brain areas was not measured in the study, thus the authors can only speculate on the reasons for the enhanced cognitive function.

In addition to these ‘physiological’ mechanisms, more general ‘psychological’ mechanisms have also been postulated to mediate the effect between exercise and cognitive function. For example, Brisswalter et al (2002) have suggested that increases in arousal, occurring as a result of exercise, enhance cognitive function. Furthermore, exercise has also been shown to improve mood, which in turn improves cognitive function. Specifically, in their meta-analysis, Reed & Buck (2009) concluded that exercise had a significant positive
effect on mood (overall ES = 0.57). Therefore, it appears that the combination of improved mood and increased arousal following exercise could contribute to enhanced cognitive function.

Whilst not of direct relevance here, evidence from animal studies has been used to postulate mechanisms for the longer term effects of exercise on cognitive function. As reviewed by Davis & Lambourne (2009), evidence suggests that exercise stimulates neural tissue, which activates growth factors in the brain, promoting neurogenesis (growth of new neurons) and angiogenesis (growth of new capillaries) (Dishman et al, 2006). Logically, such changes could play a role in enhancing cognitive function. However, whilst these mechanisms are unlikely to play a role in the acute effects of exercise on cognition, they do suggest that brain structures can be affected by exercise.

It is clear from the above review that whilst a number of potential mechanisms have been postulated, little is currently known regarding the mechanisms responsible for mediating exercise induced effects on cognitive function. Therefore it is apparent that more research is required in this area to further explore the potential mechanisms. From this review, five main avenues appear to be open for such research, namely: the effects of exercise on the delivery of nutrients and removal of waste products from the brain; the role of lactate within the brain; the effects of exercise on signalling (event related potentials) within the brain; the effects of certain types of exercise on pre-activation of certain areas of the brain; and finally, the effects of exercise on psychological variables such as mood and arousal.
2.8: Recommendations for Future Research Concerning Exercise Interventions and Cognitive Function

From reviewing the literature to date, the following recommendations for future research assessing the acute effects of exercise on cognitive function can be made:

- Where possible studies should employ a counter-balanced cross-over study design, to eliminate the role of confounding variables in influencing study outcomes. However, where cross-sectional design is required, potential confounding variables must be carefully controlled.

- Studies should focus on specific populations, especially with regards to age and the dichotomy between children and adolescents. Another factor considered by some studies to date is the physical fitness of the participants, but findings indicated that physical fitness does not affect the exercise induced effects on cognitive function (Zervas et al, 1991; Stroth et al, 2009), thus suggesting studies can include participants of heterogeneous fitness levels.

- A range of pre-validated cognitive function tests should be selected, which examine specific cognitive functions and are suitable for the study population. Where possible, studies should also employ a battery of tests assessing multiple components of cognitive function, allowing the greatest claims to be made regarding the effects on overall cognitive function. An opportunity for participants to familiarise themselves with the tests should be provided and where possible, computer based test assessing speed and accuracy should be used.

- The timescale of the acute effects of exercise on cognitive function need to be examined. Much of the work to date has examined the effects during or immediately post-exercise, with little known about the delayed effects of exercise (e.g. 60-120 min
following exercise), which are of greater practical importance in everyday school settings.

- Diet should be controlled on the day of the experimental trials, especially when conducting a crossover design where participants undertake repeated trials. In these cases, diet should be recorded and repeated for subsequent trials.

- Further work needs to be conducted to examine the effects of the exercise characteristics, with particular interest in the relationship between the duration and intensity of exercise and subsequent cognitive function. Such work may allow researchers to confirm or refute the ‘inverted U hypothesis’ for the relationship between exercise intensity and cognitive function, and its applicability to young people. To achieve this, studies should include a physiological measure of the intensity of the exercise used (e.g. heart rate or oxygen uptake). Furthermore, work is required to extend the findings of Budde et al (2008) and examine whether specific modes of exercise (e.g. those activating certain brain areas) are particularly beneficial for subsequent cognitive function.
Chapter III

General Methods

3.1: Introduction

This chapter provides an account of the general methodologies employed during the studies presented in this thesis (chapters IV – VII) and is split into 6 sections. The first section (section 3.2) explains the procedures for participant recruitment and gaining informed consent. The second section (section 3.3) outlines the preliminary measures that were made during familiarisation for each of the studies. The following 3 sections (sections 3.3, 3.4 and 3.5) explain the procedures that were conducted during the main experimental trials, namely the cognitive function tests, mood questionnaire and capillary blood samples. The final section (section 3.6) outlines the statistical analysis that was conducted on the data collected.

3.2: Participant Recruitment

Each of the studies presented in this thesis was conducted in secondary schools in and around Loughborough, UK. Prior to participant recruitment for each study, clearance was obtained from Loughborough University Ethical Advisory Committee and all researchers involved in the testing days underwent full Criminal Record Bureau checks. In the first instance, contact was made with the head teacher of the schools to inform the school of the purposes of the study and what was involved should they decide to participate. Once a school had agreed to participate, in line with the British Education Research Authority guidelines for
school-based research, school level consent was obtained from head teachers in writing prior to commencing each study. Subsequently, the purpose of the study and experimental procedures were explained to the potential participants by the researchers and potential participants were allowed an opportunity to ask any questions.

Any potential participants who decided they wanted to participate in the study were then provided with written information which was taken home to parents or guardians, which included contact details of the researchers should parents or guardians want to ask any questions (see appendix A1). This information was accompanied by an informed consent form, which participants’ parents or guardians had to complete and return to researchers before their child could participate (see appendix A2). Furthermore, a health screen questionnaire (see appendix A3) was provided to be completed by participants in conjunction with their parents or guardians. Participants with any health conditions which could pose an undue risk or bias the study results were excluded from participating in the study. It was also made clear to participants that they could withdraw from the study at any time without providing a reason.

3.3: Preliminary Measurements and Familiarisation

Prior to each participants’ first trial, preliminary measurements were made. A number of anthropometric measurements were taken, namely height, body mass and waist circumference. Furthermore, participants were provided with an opportunity to familiarise themselves with the cognitive function tests. Specifically, the purpose of each cognitive function test was explained to participants and a demonstration given. Participants then completed the full battery of cognitive tests, lasting approximately 15-20 min (see section...
3.4. Throughout the familiarisation process, researchers were available for participants to clarify any component of the cognitive function tests they did not fully understand. Participants also completed the mood questionnaire and had a capillary blood sample taken (see sections 3.5 and 3.6 respectively), following which there was an opportunity for the participants to ask researchers any questions regarding their participation in the study.

Height was measured using a Leicester Height Measure (Seca, Hamburg, Germany), accurate to 0.1 cm. Body mass was measured using a Seca 770 digital scale (Seca, Hamburg, Germany), accurate to 0.1kg. These measures allowed the determination of Body Mass Index (BMI), calculated by dividing body mass [kg] by the square of the height [m²]. Waist circumference was measured at the narrowest point of the torso between the xiphoid process of the sternum and the iliac crest, to the nearest 0.1cm.

### 3.4: Cognitive Function Tests

For each study, a battery of cognitive function tests was administered via a laptop computer. The cognitive function tests consisted of the visual search test, Stroop test and Sternberg paradigm (in addition, in chapter V the Flanker task was added to the testing battery), as can be seen in table 3.1.

<table>
<thead>
<tr>
<th>Order</th>
<th>Chapter IV</th>
<th>Chapter V</th>
<th>Chapter VI</th>
<th>Chapter VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Visual Search Test</td>
<td>Visual Search Test</td>
<td>Visual Search Test</td>
<td>Visual Search Test</td>
</tr>
<tr>
<td>2</td>
<td>Stroop Test</td>
<td>Stroop Test</td>
<td>Stroop Test</td>
<td>Stroop Test</td>
</tr>
<tr>
<td>3</td>
<td>Sternberg Paradigm</td>
<td>Sternberg Paradigm</td>
<td>Sternberg Paradigm</td>
<td>Sternberg Paradigm</td>
</tr>
<tr>
<td>4</td>
<td>N/A</td>
<td>Flanker Task</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 3.1: Cognitive function tests completed in the experimental studies.
Prior to the studies being completed, the cognitive function tests were piloted to ensure their suitability for an adolescent population. At this stage, the Rapid Visual Information Processing (RVIP) test was excluded from the studies because it was too complex for the adolescents to complete to a satisfactory standard.

The instructions for each of the cognitive function tests were verbally explained to participants and were also displayed on the screen prior to each test. Participants were also provided with an opportunity to ask questions to clarify any aspects of the cognitive function tests. An example of a screenshot from each of the cognitive function tests can be found in appendix B.

3.4.1: Visual Search Test

The visual search test, a test of perception, consisted of two levels (baseline and complex), each consisting of 21 stimuli. On each level, participants were instructed to respond as quickly as possible to the stimuli by pressing the space bar on the keyboard. In both levels there were 21 different locations for the stimuli, with the order of the locations randomised, thus allowing a standardised test. At the start of each level, the instructions explaining the test level appeared on the screen. Following the instructions, there were 3 practice stimuli for which the data were discarded, which allowed participants to re-familiarise themselves with the test level (negating any potential learning effects) and fully focus on the task in hand.

The stimuli in the baseline level were triangles drawn in solid green lines on a black background, providing a measure of simple visuo-motor speed. The complex level had random green dots covering the screen, which were redrawn every 250 ms to induce the
visual effect of a flickering background, acting as a background distractor. The target triangles were drawn with a few dots on each line and the density of these dots increased until the participant responded (the lines become denser until a response is registered). This provided a measure of complex visual processing. The variables of interest on both levels were the response times of the correct responses and the percentage of correct responses made.

3.4.2: Stroop Test

The Stroop test measures the sensitivity to interference and the ability to suppress an automated response (Stroop, 1935) and is commonly used to assess selective attention (van Zomeren & Brouwer, 1992). The Stroop test consisted of two levels (baseline and complex). Both levels involved a test word being placed in the centre of the screen, with the target and distractor presented randomly on the right or left of the test word. The target position was counterbalanced for the left and right side within each level of the test. The participant was asked to respond as quickly as possible, using the left and right arrow keys, to identify the position of the target word. Each test level was preceded by 6 practice stimuli for which the data were discarded and participants were provided with feedback as to whether their response was correct. These practice stimuli allowed participants to re-familiarise themselves with the test level (negating any potential learning effects) and fully focus on the task in hand. Following the practice stimuli, the instructions were presented on the screen again. Once the test started, no feedback was provided regarding whether participants’ responses were correct.
The baseline level contained 20 stimuli, where the test word was printed in white and the participant had to select the target word, from the target and distractor, which were also printed in white. The complex (colour-interference) level contained 40 stimuli and involved the participant selecting the colour the test word was written in, rather than the actual word (which was an incongruent colour), again using the right and left arrow keys to identify the target. The choices remained on the screen until the participant responded. The variables of interest were the response times of the correct responses and the percentage of correct responses made.

3.4.3: Sternberg Paradigm

The Sternberg Paradigm (Sternberg, 1969) is a test of working memory and has three levels. Each level used a different working memory load; one, three or five items. On the baseline (number) level, the target was always the number ‘3’. This level contained 16 stimuli and provides a measure of basic information processing speed. The three- and five-item levels had target lists of three and five letters respectively, each containing 32 stimuli. At the start of each level, the target items were displayed together with instructions to press the right arrow key if the stimulus was a target item and the left arrow key otherwise. This was followed by 6 practice stimuli for which the data were discarded and participants were provided with feedback as to whether their response was correct. These practice stimuli allowed participants to re-familiarise themselves with the test level (negating any potential learning effects) and fully focus on the task in hand. At the end of the practice stimuli, the instructions and target items were presented on the screen again. Once the test started, no feedback was provided regarding whether participants’ responses were correct.
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The correct responses were counterbalanced on each level between the right and left arrow keys. The choice stimuli were presented on the centre of the screen with an inter-stimulus interval (ISI) of 1 second, during which the screen was blank. The choices remained on the screen until the participant responded. The variables of interest were response times of the correct responses and the percentage of correct responses made.

3.4.4: Flanker Task

The Flanker task assesses aspects of attention and has two types of stimuli (congruent and incongruent). For congruent stimuli, five arrows appear on the screen all pointing in the same direction (left or right). The participant selected the arrow key in the same direction the arrows were pointing. For incongruent stimuli, the arrows point in different directions and the participant selected the arrow key that matched the direction the central arrow pointed. The Flanker task was preceded by 6 practice stimuli (3 congruent and 3 incongruent) for which the data were discarded and participants were provided with feedback as to whether their response was correct. These practice stimuli allowed participants to re-familiarise themselves with the test (negating any potential learning effects) and fully focus on the task in hand. Once the test started, no feedback was provided regarding whether participants’ responses were correct.

On both levels, the arrows were presented in green on a black background, after a varied delay of 400 to 4000 ms. during which the screen was blank. The items remained on the screen until the participant responded. The variables of interest were the response times of the correct responses and the percentage of correct responses made.
3.5: Mood Questionnaire

The mood questionnaire was a modified version of the ‘Activation-Deactivation Check List’ (ADACL) short form (Thayer, 1989) (see appendix C). The 20 item questionnaire was split into four components of mood; energy, tiredness, tension and calmness, each having five corresponding adjectives on the questionnaire. The original ADACL short form was piloted in an adolescent population and subsequently five of the adjectives were changed to ensure suitability for the study population. The adjectives used and their corresponding components of mood were; energy: active, energetic, alert, lively and wide-awake; tiredness: sleepy, tired, drowsy, exhausted and fatigued; tension: anxious, nervous, fearful, worried and tense; and calmness: restful, calm, at-rest, laid-back and quiet.

The scoring system was also slightly modified, with participants asked to respond on a scale of 1 to 5 regarding how they felt at that moment in time (where 1: definitely do not feel, 3: unsure, 5: definitely feel). The scores on the adjectives for each component of mood were summed, providing an overall score for each component.

In addition, visual analogue scales (VAS) were used to provide a measure of participants’ hunger and fullness in all chapters, whilst in chapters V, VI and VII a VAS assessing concentration was also added. The VAS consisted of a 10 cm line from one extreme to the other (i.e. not at all hungry to very hungry, not at all full to very full, and can concentrate very well to cannot concentrate at all), with participants indicating the point on the line that applied to them at that moment in time. Both the ADACL and VAS allow comparisons between time points.
3.6: Capillary Blood Sampling and Analysis

3.6.1: Collection and Treatment of Capillary Blood Samples

In chapter IV, the only variable of interest from the capillary blood samples was blood glucose concentration and thus an Accutrend hand-held analyser was used, as described in section 4.2.6. However, in chapters V, VI and VII, blood glucose, plasma insulin and blood lactate (chapters VI and VII only) concentrations were determined. Therefore, the method for collecting capillary blood samples and subsequent analysis was different to that employed in chapter IV and is described here.

When examining the differences in glycaemic and insulinaemic responses between meals, it has been suggested that capillary blood samples are preferred to venous blood samples because they are more sensitive to glycaemic responses and show a lower between subject variation (Wolever et al, 1991; Kuwa et al, 2001; Wolever, 2003; Brouns et al, 2005). Furthermore, capillary blood samples were preferred in the studies presented in this thesis due to ethical constraints in young people.

To ensure adequate blood flow for sampling, participants’ hands were warmed via submersion in warm water to increase capillary blood flow. Participants then dried their hands and the area was prepared using an isopropyl alcohol wipe. A Unistik single use lancet (Unistik Extra, 21G gauge, 2.0mm depth, Owen Mumford Ltd., UK) was used and the blood collected into two 300 µl EDTA coated microvettes (Sarstedt Ltd., UK).

For determination of blood glucose and blood lactate concentrations, two 25 µl whole blood samples were removed using 25 µl plain pre-calibrated glass pipettes (Hawksley Ltd., UK), immediately deproteinised in 250 µl of 2.5% ice cooled perchloric acid in 1.5 ml plastic vials and centrifuged at 7000 rpm for 4 minutes (Eppendorph 5415C, Hamburg, Germany).
For determination of plasma insulin concentration, the remaining whole blood was also centrifuged at 7000 rpm for 4 minutes (Eppendorf 5415C, Hamburg, Germany) and the plasma removed and placed into 500 µl plastic vials. All samples were frozen at -20 ºC until analysis.

3.6.2: Analysis of Capillary Blood Samples

Blood glucose concentrations were determined in duplicate using a commercially available kit (GOD-PAP method, GL 2610, Randox, Ireland). Plasma insulin concentrations were determined using an enzyme-linked immuno-sorbent assay (ELISA) (Mercodia Ltd., Sweden). Incremental area under the curve (IAUC) for blood glucose and plasma insulin was calculated using the method described by Wolever & Jenkins (1986). Blood lactate concentrations were determined in duplicate using an enzymatic method described by Maughan (1982).

3.6.3: Coefficients of Variation for Capillary Blood Sample Analysis

The coefficients of variation were determined using ten repeated measurements on a human blood sample. This was conducted for the hand-held device used in chapter IV, as well as the methods described above. The coefficient of variation was calculated as follows:

\[
\text{Coefficient of Variation (CV)} = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100\%
\]

(Cohen & Holliday, 1982)
Table 3.2: Coefficients of variation for the analysis of capillary blood samples

<table>
<thead>
<tr>
<th>Variable</th>
<th>Method</th>
<th>n</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>CV [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>Accutrend</td>
<td>10</td>
<td>4.86 mmol.L(^{-1})</td>
<td>0.14 mmol.L(^{-1})</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>Randox</td>
<td>10</td>
<td>4.97 mmol.L(^{-1})</td>
<td>0.06 mmol.L(^{-1})</td>
<td>1.14</td>
</tr>
<tr>
<td>Insulin</td>
<td>ELISA</td>
<td>10</td>
<td>171.5 pmol.L(^{-1})</td>
<td>3.18 pmol.L(^{-1})</td>
<td>1.85</td>
</tr>
<tr>
<td>Lactate</td>
<td>Enzymatic</td>
<td>10</td>
<td>2.22 mmol.L(^{-1})</td>
<td>0.04 mmol.L(^{-1})</td>
<td>1.80</td>
</tr>
</tbody>
</table>

3.7: Test Meals

3.7.1: Self-Selected Breakfasts

In chapters IV and VI, participants were able to choose a self-selected breakfast. A range of breakfast foods were provided, from which participants chose *ad libitum*. Broadly, the breakfast could be classified into: cereals (Cornflakes, Coco Pops, Frosties, Bran Flakes, Muesli and Weetabix, all available with semi-skimmed milk), toast (a choice of white or brown bread along with butter, margarine and strawberry and raspberry jam), fruit (apples and bananas), yoghurts (strawberry and raspberry) and fruit juices (orange and apple). The quantity of food taken by each participant was recorded and any leftovers were weighed using a Salter 1029 WHDRT scale (Salter, Hamburg, Germany) to allow determination of the breakfast consumed by each participant. The breakfast consumed was analysed for total energy content (kcal) and for the amount of carbohydrate (g), protein (g) and fat (g).

3.7.2: High and Low Glycaemic Index Breakfasts

In chapters V and VII, high GI and low GI breakfasts were provided for participants. The high GI breakfast consisted of cornflakes, milk, toasted white bread and margarine. The
low GI breakfast consisted of muesli, milk and apple. The high and low GI breakfasts both contained 1.5 g.kg\(^{-1}\) body mass available carbohydrate, were isoenergetic and were matched for protein and fat content. Water (150 ml) was provided with the high GI breakfast to ensure that total water intake was the same between the breakfasts. The composition of the high and low GI breakfasts for a 50 kg participant is shown in table 3.2.

3.8: Exercise Protocol

In chapters VI and VII, participants completed a mid-morning bout of exercise on the exercise trial, whereas they continued to rest on the resting trial. The exercise performed was a modified version of the Multi-Stage Fitness Test (Ramsbottom et al, 1988). The exercise protocol consisted of 10 repetitions of stage one (each consisting of 7 x 20 m shuttle runs at 8.0 km.hr\(^{-1}\)), with a 30 second rest between each repetition. Prior to the exercise, participants were fitted with a Polar Wearlink heart rate monitor and a Polar S610i watch (Polar, Finland). Immediately following each repetition, heart rate was recorded. If participants’ heart rate reached 190 beats.min\(^{-1}\) (approximately 90% maximum heart rate in this population), participants were instructed to stop running and to walk for the remainder of the test. The duration of the exercise was chosen so it was sufficiently brief to fit into a normal school morning and reflected adolescents’ usual physical activity patterns. Therefore, the exercise protocol has potential practical application to be incorporated into the school morning.
### Table 3.2: Composition of high and low GI breakfasts for a 50 kg participant

<table>
<thead>
<tr>
<th>Food Items</th>
<th>High GI (g)</th>
<th>Low GI (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cornflakes (^a)</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>white bread (^b)</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>margarine (^c)</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1% fat milk (^d)</td>
<td>216</td>
<td>217</td>
</tr>
<tr>
<td>muesli (^e)</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>apple (^f)</td>
<td></td>
<td>150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Macronutrients</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kcal)</td>
<td>422</td>
<td>420</td>
</tr>
<tr>
<td>CHO (g)</td>
<td>75.0</td>
<td>75.0</td>
</tr>
<tr>
<td>Fat (g)</td>
<td>7.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Protein (g)</td>
<td>14.3</td>
<td>15.5</td>
</tr>
<tr>
<td>Food Quantity (g)</td>
<td>319</td>
<td>442</td>
</tr>
</tbody>
</table>

| Glycaemic Index \(^g\)   | 72         | 48         |
| Glycaemic Load \(^h\)    | 54         | 36         |

\(^a\) Cornflakes (Kelloggs Ltd., UK)
\(^b\) Lightly toasted white bread (Kingsmill soft white thick slice, UK)
\(^c\) Margarine (Flora Original, UK)
\(^d\) 1% fat milk (Sainsbury’s Ltd., UK)
\(^e\) Muesli (Alpen no added sugar, Weetabix Ltd., UK)
\(^f\) Apple (Braeburn apple)

\(^g\) Calculated by the method described by Wolever & Jenkins (1986) with GI values taken from Foster-Powell et al (2002)
\(^h\) Calculated by the method described by Foster-Powell et al (2002)
3.9: Statistical Analysis

A variety of statistical procedures were used to analyse the data presented in chapters IV – VII. The data from the cognitive function tests were analysed using R (www.r-project.org, version 2.9.1). In chapters IV – VI, the cognitive function data were analysed using linear mixed effects models, corrected for repeated measures with a random effect for each participant. Response time analyses were conducted using the nlme package and accuracy analyses were conducted using the lme4 package with a binomial outcome data distribution. In chapter VII, the cognitive function data were analysed using analysis of variance (ANOVA), also conducted using R.

All other (mood, blood glucose, plasma insulin, blood lactate and heart rate) data were analysed using SPSS (version 16, Chicago, IL; chapters IV and V) or PASW Statistics (version 18, Chicago, IL; chapters VI and VII), using a variety of statistical techniques, including; ANOVA, paired sample t-tests and independent sample t-tests, where appropriate. A more detailed description of the statistical analysis conducted is provided in each chapter.
Chapter IV

Breakfast Consumption and Cognitive Function in Adolescent School Children

4.1: Introduction

It is often stated that breakfast is the most important meal of the day. However, young people are more likely to skip breakfast than any other meal (Dwyer et al., 2001), with only just over 50% of young people aged 6 to 11 regularly eating breakfast (Mahoney et al., 2005). Furthermore, breakfast skipping in young people and adolescents is reported to be increasing in prevalence (Siega-Riz et al., 1998). This is of particular concern because breakfast consumption has a number of positive effects in young people including; improving dietary adequacy, a decreased risk of being overweight or obese and improved cognitive function (Pearson et al., 2009). The present study focuses on the last of these effects, the effects of breakfast consumption and omission on cognitive function in adolescent schoolchildren.

Numerous studies have been conducted in younger children (typically 8-11 years old) with findings indicative of a positive effect of breakfast consumption on cognitive function (Pollitt et al., 1981; Mahoney et al., 2005; Ingwersen et al., 2007). However, evidence regarding the effects of breakfast consumption on cognitive function in adolescents is equivocal. Of the three studies conducted in adolescent populations, two early studies suggested there was no effect of breakfast consumption on adolescents’ cognitive function (Dickie & Bender, 1982; Cromer et al., 1990). However, these studies employed cross-
sectional study designs and limited tests of cognitive function, thus their findings must be interpreted cautiously.

More recently, using a crossover study design, Widenhorn-Müller et al (2008) found that the accuracy of visuospatial memory was enhanced immediately following breakfast when compared to breakfast omission, whereas there was no effect of breakfast consumption on the accuracy of verbal memory or attention. Interestingly, there were also a number of positive effects on mood following breakfast consumption, such as increases in self-report awareness and males also reported feeling more positive (Widenhorn-Müller et al, 2008). However, the use of a standardised breakfast may have resulted in different effects between participants due to differences in palatability of the meal, food preferences and in the nutritional content of the breakfasts provided relative to body mass. Furthermore, the lack of an effect of breakfast consumption on verbal memory and attention could be due to the cognitive testing taking place immediately after breakfast, whereas it is suggested the beneficial effects of breakfast consumption become more apparent later in the morning (Hoyland et al, 2009).

Despite the lack of studies conducted in adolescent populations, it is suggested adolescents are particularly worthy of study for four main reasons, described in detail in section 2.2.2. In brief, due to the physiological differences between adolescents and younger children, their responses may be different thus require separate investigation (Cromer et al, 1990; Kanarek, 1997). Furthermore, the academic work completed by adolescents is of greater complexity and importance than in younger children, and due to the effect of cognitive function on academic achievement (section 2.2.1.3), any effects of breakfast consumption on cognitive function are of great interest (Cromer et al, 1990). Finally, evidence also suggests that adolescents are a population more likely to skip breakfast due to
peer and media pressure to maintain a slender body (Kanarek, 1997) thus the effects of this practice are important to document. In spite of the importance of the research in this area in adolescent populations, a recent review indicates that there is a need for more studies which examine the effects of breakfast consumption across a range of dimensions of cognitive function in adolescent populations (Hoyland et al, 2009).

Whilst some of the literature in adult populations has attempted to explain mechanistically the improvement in cognitive function observed after breakfast consumption, such work has not been conducted in children or adolescents. Glucose is the only fuel that can be used by the brain and thus is crucial for cognitive function. Research in adults indeed suggests that higher blood glucose concentrations improve memory (Benton & Sargent, 1992) and performance on the Stroop test (Dye et al, 2000), but the effects of breakfast consumption on blood glucose concentrations and subsequent cognitive function in an adolescent population have not been examined.

Therefore, the aim of the present study is to examine the effects of an ad libitum breakfast on the cognitive function, mood and blood glucose concentration of adolescents (12-15 years old) using a randomised crossover design. The use of an ad libitum breakfast should allow participants to consume a breakfast similar to their habitual breakfast intake, thus allowing the findings to be applied to everyday settings. The study will employ a battery of cognitive function tests across a wider range of dimensions than in previous studies (assessing visual perception, attention and working memory) and furthermore, by measuring blood glucose concentration, an insight into potential mechanisms for an effect of breakfast consumption on cognitive function in an adolescent population may be possible.
4.2: Methodology

4.2.1: Participant Characteristics

Sixty children in year 8 (30 male and 30 female) and thirty-six children in year 10 (6 male and 30 female) were recruited to participate in the study. Of the ninety-six participants, fifty-three (55%) reported consuming breakfast every day, thirty-four (35%) reported consuming breakfast regularly (between one and six times per week) and 9 (10%) reported that typically they did not consume breakfast. During familiarisation, simple measures of height, body mass and waist circumference were taken using the methods described in detail in section 3.3. For descriptive purposes, the anthropometric characteristics of the participants are provided in table 4.1.

**Table 4.1: Anthropometric characteristics of participants.**

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Age [yrs]</th>
<th>Height [cm]</th>
<th>Body Mass [kg]</th>
<th>BMI [kg/m²]</th>
<th>Waist Circumference [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year 8</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>30</td>
<td>12.4±0.5</td>
<td>157.2±8.4</td>
<td>48.1±9.2</td>
<td>19.3±2.8</td>
<td>66.6±6.8</td>
</tr>
<tr>
<td>Female</td>
<td>30</td>
<td>12.6±0.5</td>
<td>158.2±7.3</td>
<td>48.4±9.5</td>
<td>19.2±2.8</td>
<td>64.7±6.4</td>
</tr>
<tr>
<td>Overall</td>
<td>60</td>
<td>12.5±0.5</td>
<td>157.7±8.4</td>
<td>48.2±9.3</td>
<td>19.3±2.8</td>
<td>65.7±6.6</td>
</tr>
<tr>
<td><strong>Year 10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6</td>
<td>14.3±0.5</td>
<td>171.2±11.9</td>
<td>62.4±12.6</td>
<td>21.1±1.9</td>
<td>72.6±6.7</td>
</tr>
<tr>
<td>Female</td>
<td>30</td>
<td>14.7±0.5</td>
<td>163.3±5.5</td>
<td>57.9±9.1</td>
<td>21.7±3.2</td>
<td>69.3±6.1</td>
</tr>
<tr>
<td>Overall</td>
<td>36</td>
<td>14.7±0.5</td>
<td>164.7±7.3</td>
<td>58.7±9.7</td>
<td>21.6±3.0</td>
<td>69.8±6.2</td>
</tr>
<tr>
<td>Combined</td>
<td>96</td>
<td>13.3±1.2</td>
<td>160.3±8.3</td>
<td>52.1±10.7</td>
<td>20.1±3.0</td>
<td>67.2±6.8</td>
</tr>
</tbody>
</table>

All values are mean ± standard deviation.
4.2.2: Study Design

The study was approved by Loughborough University Ethical Advisory Committee. Consent was gained from participants using the methods described in detail in section 3.2. In brief, a written consent from and health screen questionnaire was completed by participants’ parents or guardians prior to participation in the study. In addition, on each testing day participants completed a willingness to participate form.

Each participant undertook a familiarisation session which preceded the first of the two experimental trials by seven days. During familiarisation, the protocol of the study was explained to participants and they were familiarised with the methods involved. The study employed a randomised crossover design, with participants blinded against trial condition until arrival at school on their first day of testing. The experimental trials consisted of one trial where breakfast was provided upon arrival at school (breakfast trial) and one trial where no breakfast was provided until completion of the protocol (no breakfast trial), thus participants acted as their own controls. Trials were scheduled seven days apart and participants reported to school at the normal time, having followed an overnight fast from 10 pm the evening before the trial. The experimental protocol is shown in figure 4.1.

**Figure 4.1:** Experimental Protocol
Participants were recruited from five local schools. For descriptive purposes, the Index of Multiple Deprivation (an indicator of socio economic status) for each of the schools can be seen in table 4.2. Upon arrival at school participants were provided with breakfast if completing the breakfast trial. Participants were given 15 min to consume breakfast. After breakfast (or after 15 min resting on the no breakfast trial), participants completed the mood questionnaire and cognitive function tests. Following the tests, the subgroup who were providing a capillary blood sample had this measure taken. Participants then returned to normal lessons for approximately 90 min, after which they reported back to investigators and repeated the mood questionnaire, cognitive function tests (120 min after baseline measures) and provided a capillary blood sample (if appropriate). The use of a 120 min interval between testing sessions is based upon previous findings which indicate this is a sufficient period for the benefits of breakfast consumption to become apparent in young people (Wesnes et al, 2003; Micha et al, 2006; Benton et al, 2007). All participants were then fed upon completion of the trial.

**Table 4.2: Index of Multiple Deprivation of the schools recruited**

<table>
<thead>
<tr>
<th>School</th>
<th>Index of Multiple Deprivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24787</td>
</tr>
<tr>
<td>2</td>
<td>12082</td>
</tr>
<tr>
<td>3</td>
<td>22569</td>
</tr>
<tr>
<td>4</td>
<td>24629</td>
</tr>
<tr>
<td>5</td>
<td>24541</td>
</tr>
</tbody>
</table>
**4.2.3: Breakfast**

In this study, participants were provided with a buffet and selected breakfast from these foods *ad libitum*, as described in section 3.7.1. The quantity of food taken by each participant was weighed and any leftovers were weighed to allow determination of the breakfast consumed by each participant. The breakfast consumed was analysed for total energy content (kcal) and for the amount of carbohydrate (g), protein (g) and fat (g). The energy content and composition of the breakfast consumed is shown in table 2.3.

**Table 4.3: Breakfast consumed by participants**

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Energy [kcal]</th>
<th>Carbohydrate [g]</th>
<th>Protein [g]</th>
<th>Fat [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>36</td>
<td>589±208</td>
<td>107.6±40.2</td>
<td>14.0±5.4</td>
<td>10.7±6.1</td>
</tr>
<tr>
<td>Female</td>
<td>60</td>
<td>406±169</td>
<td>72.8±30.3</td>
<td>9.3±4.9</td>
<td>8.2±5.1</td>
</tr>
</tbody>
</table>

| p-value for gender comparison | 0.001 | 0.001 | 0.002 | 0.079 |

All values are mean ± standard deviation.

*a* gender comparison performed using independent samples t-test.

**4.2.4: Mood Questionnaire**

The modified version of the ‘Activation-Deactivation Check List’ (ADACL), as described in detail in section 3.5, was completed by participants immediately prior to completing the cognitive function tests. The mood questionnaire provided a measure of participants’ self-report energy, tiredness, tension and calmness. In addition, two visual analogue (VAS) scales were used to provide a measure of participants’ hunger and fullness. Both the ADACL and the VAS scales allow comparisons between time points.
### 4.2.5: Cognitive Function Tests

The battery of cognitive function tests was administered via a laptop computer immediately following breakfast and again 120 min later. The battery of tests for this study consisted of the visual search test, the Stroop test and the Sternberg Paradigm, which are described in detail in section 3.4.

### 4.2.6: Capillary Blood Sampling

In a subgroup of 30 year 8 students (14 male and 16 female) and 30 year 10 students (4 male and 26 female), a capillary blood sample was taken to allow determination of blood glucose concentration. Separate parental consent was obtained prior to participants providing a capillary blood sample. An Accu-check Safe-T-pro plus single use lancet (Roche, Manheim, Germany) was used and a drop of blood placed onto the test strip. The test strip was placed into an Accutrend Plus GCTL analyser (Roche, Mannheim, Germany) to allow instant determination of blood glucose concentration (12 seconds). The analyser was calibrated using the Accutrend control solutions (4.5 and 11.4 mmol.L\(^{-1}\)), and was accurate to 0.1 mmol.L\(^{-1}\) in the range of 1.1 to 33.3 mmol.L\(^{-1}\).

### 4.2.7: Statistical Analysis

The mood and blood glucose data were analysed using SPSS (Version 16, SPSS Inc., Chicago, Il, USA) via two-way Analysis of Variance (ANOVA) for repeated measures (trial by session time). Data are reported as mean ± S.E.M..
The cognitive function data were analysed using R (www.r-project.org, version 2.9.1). Linear mixed effects models were used to analyse the data, corrected for repeated measures with a random effect for each participant. Response time analyses were performed using the nlme package and accuracy analyses were performed with the lme4 package with a binomial outcome data distribution. All analyses were conducted using a three-way trial by session time by test level interaction. In addition, where appropriate, the two-way trial by session time and trial by test level interactions were examined, as well as the main effects of trial, session time and test level. For all analysis, significance was set as p < 0.05.

4.3: Results

For each dimension of mood and cognitive function, there was no effect of the year group of the participants or the trial order on participants’ responses (all p > 0.05); thus all participants’ responses were analysed together. Interestingly, despite differences in the schools’ indices of multiple deprivation, the responses of participants from each of the schools was not significantly different (all p > 0.05); thus all participants responses were analysed together. Furthermore, order effects were examined and were non-significant for each dimension of mood and cognitive function (all p > 0.05).

4.3.1: Mood

4.3.1.1: Energy

Analysis revealed a main effect of trial ($F_{(1,94)} = 82.8$, p < 0.001), with self-report energy significantly higher on the breakfast trial compared to the no breakfast trial (18.1 vs.
Chapter IV: Breakfast Consumption and Cognitive Function

14.1 respectively). However, there was no main effect of session time (p = 0.097) and there was no difference in the change in self-report energy across the morning on the breakfast and no breakfast trials (trial by session time interaction, p = 0.097).

4.3.1.2: Tiredness

Analysis revealed a main effect of trial (F(1,95) = 41.8, p < 0.001), with self-report tiredness higher on the no breakfast trial compared to the breakfast trial (13.7 vs. 10.8 respectively). There was also a main effect of session time (F(1,95) = 26.1, p < 0.001) with self-report tiredness higher early in the morning when compared to the later morning session (13.0 vs. 11.5, respectively). However, there was no difference in the change in self-report tiredness across the morning between the breakfast and no breakfast trials (trial by session time interaction, p = 0.076).

4.3.1.3: Tension

Self-report tension was not different between the breakfast and no breakfast trials (main effect of trial, p = 0.100), nor between the early and late morning sessions (main effect of session time, p = 0.123). Furthermore, the pattern of change in self-report tension across the morning was not different between the breakfast and no breakfast trials (trial by session time interaction, p = 0.278).
4.3.1.4: Calmness

There was no difference in self-report calmness between the breakfast and no breakfast trials (main effect of trial, \( p = 0.215 \)). However, there was a main effect of session time (\( F_{(1,95)} = 24.2, \ p < 0.001 \)) with participants reporting a greater level of calmness early in the morning, compared to later in the morning (15.9 vs. 14.6 respectively). The pattern of change in self-report calmness across the morning was similar between the breakfast and no breakfast trials (trial by session time interaction, \( p = 0.397 \)).

4.3.1.5: Hunger

Analysis revealed a main effect of trial on self-report hunger (\( F_{(1,94)} = 240.5, \ p < 0.001 \)). As expected, self-report hunger was higher on the no breakfast trial compared to the breakfast trial (8.0 vs. 3.6 respectively). There was also a main effect of session time (\( F_{(1,94)} = 114.4, \ p < 0.001 \)), with self-report hunger higher later in the morning when compared to the early morning session (6.7 vs. 4.8 respectively). Furthermore, self-report hunger increased on both the breakfast and no breakfast trials, though the increase was greater on the breakfast trial (trial by session time interaction, \( F_{(1,94)} = 33.8, \ p < 0.001 \), figure 4.2).
Figure 4.2: Self-report hunger across the morning on the breakfast (BR) and no breakfast (NB) trials. Data are mean ± S.E.M.

(trial by session time interaction, p < 0.001)

4.3.1.6: Fullness

As expected, the results from the fullness VAS scale show the opposite effects to that of hunger. Analysis revealed a main effect of trial ($F(1,94) = 290.3, p < 0.001$) with self-report fullness higher on the breakfast trial when compared to the no breakfast trial (6.0 vs. 1.6 respectively). There was also a significant main effect of session time ($F(1,94) = 112.1, p < 0.001$) with higher self-report fullness early in the morning compared to later in the morning (4.5 vs. 3.0 respectively). Furthermore, self-report fullness decreased across the morning on both the breakfast and no breakfast trials, though the decrease was greater on the breakfast trial (trial by session time interaction, $F(1,94) = 36.4, p < 0.001$, figure 4.3).
Figure 4.3: Self-report fullness across the morning on the breakfast (BR) and no breakfast (NB) trials. Data are mean ± S.E.M.
(trial by session time interaction, p < 0.001)

4.3.2: Cognitive Function Tests

For all timed cognitive tests the response times were first log-transformed to normalise the distributions, which exhibited the right-hand skew typical of human response times. Minimum response time cut-offs were then chosen based on what may reasonably be expected to be the fastest possible human response to the given stimuli (200 - 300ms, depending on task complexity) to exclude unreasonably fast responses, which relate to response key presses before stimuli have even been perceived. Maximum response time cut-offs were determined so as to remove unreasonably long right-hand tails for a normal distribution, corresponding to five standard deviations for each test and test level. This procedure resulted in the removal of less than 2% of responses for all tests (1.7% for Sternberg, 1% for the visual search and 0.1% for the Stroop test) and preserves more of the
data than strict standard deviation-based cut-offs, whilst at the same time approximating normally distributed response time outcomes as closely as possible.

### 4.3.2.1: Visual Search Test

*Response Times:* Only response times of correct responses were used for analysis. Using the methods previously described, responses faster than 300 ms for both test levels and slower than 1500 ms for the baseline level and 10000 ms for the complex level were removed.

There was no main effect of breakfast on response times on the visual search test (main effect of trial, \( p = 0.792 \)). As expected, students performed quicker on the baseline level than the complex level, on average by 1463 ms (main effect of test level, \( t_{(1,15507)} = 55.1, p < 0.001 \)). However, there was no difference in response times between the early and late morning sessions (main effect of session time, \( p = 0.134 \)).

The pattern of change of response times across the morning was not different between trials (trial by session time interaction, \( p = 0.268 \)) and the effects of breakfast were not different between test levels (trial by test level interaction, \( p = 0.173 \)). There was also no difference in the response times between trials across the morning on either test level (3-way trial by session time by test level interaction, \( p = 0.766 \)).

*Accuracy:* There was no main effect of breakfast on accuracy on the visual search test (main effect of trial, \( p = 0.196 \)), however participants achieved more correct responses early in the morning compared to later in the morning (main effect of session time, \( z_{(1,16427)} = 2.0, p = \))
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0.050). However, there was no main effect of test level on the proportion of correct responses (main effect of test level, \( p = 0.496 \)).

Accuracy on the baseline level of the visual search test was similar with and without breakfast, but accuracy on the complex level was greater following breakfast consumption (trial by test level interaction, \( z_{(1,16427)} = 2.7, p = 0.007 \)). However, accuracy across the morning was not affected differently by breakfast consumption and breakfast omission (trial by session time interaction, \( p = 0.505 \)). The results also suggest that accuracy on the baseline level was not different between the trials or across session times (figure 4.4a). However, accuracy on the complex level on the early morning test on the no breakfast trial was lower than at any other time point on either trial (trial by test level by session time interaction, \( z_{(1,16427)} = 2.3, p = 0.021 \), figure 4.4b).

4.3.2.2: Stroop Test

Response Times: Incorrect responses were filtered out for the analysis of response times. Using the methods previously described, responses quicker than 250 ms on both test levels and responses slower than 2500 ms on the baseline level and slower than 4000 ms on the complex level were removed.

There was no main effect of breakfast on response times on the Stroop test (main effect of trial, \( p = 0.558 \)). However, students responded on average 11 ms faster later in the morning compared to earlier in the morning (main effect of session time, \( t_{(1,21630)} = 2.8, p = \))
Figure 4.4a: Baseline level

Figure 4.4b: Complex level

Figure 4.4: Accuracy across the morning on the breakfast (BR) and no breakfast (NB) trials on the baseline (figure 4.4a) and complex (figure 4.4b) levels of the visual search test (trial by session time by test level interaction, p = 0.021)
0.005) and as expected, students responded faster on the baseline than the complex level, on average by 347 ms (main effect of test level, $t_{(1,21630)} = 17.2$, $p < 0.001$).

Response times across the morning were not different when breakfast was or was not consumed (trial by session time interaction, $p = 0.249$). Furthermore, there were no differences when breakfast was or was not consumed between test levels (trial by test level interaction, $p = 0.560$). There was also no difference in the response times between trials across the morning on either test level (3-way trial by session time by test level interaction, $p = 0.210$).

Accuracy: Students achieved more correct responses on the breakfast trial compared to the no breakfast trial (main effect of trial, $z_{(1,22973)} = 2.0$, $p = 0.041$). However, there was no difference between the proportion of correct responses made early and later in the morning (main effect of session time, $p = 0.923$). As expected, students achieved more correct responses on the baseline level than the complex level (main effect of test level, $z_{(1,22973)} = 4.2$, $p < 0.001$).

Accuracy on the no breakfast trial decreased across the morning whereas on the breakfast trial accuracy was better maintained across the morning (trial by session time interaction, $z_{(1,22973)} = 2.3$, $p = 0.022$, figure 4.5). Accuracy was similar on the baseline level on both the breakfast and no breakfast trials, but accuracy on the complex level tended to be lower on the no breakfast trial compared to the breakfast trial. However, this did not quite reach statistical significance (trial by test level interaction, $z_{(1,22973)} = 2.0$, $p = 0.051$). There was also no significant difference in accuracy between trials across the morning between test levels (3-way trial by session time by test level interaction, $p = 0.260$).
Figure 4.5: Accuracy across the morning on the breakfast (BR) and no breakfast (NB) trials on the Stroop test (trial by session time interaction, p = 0.022)

4.3.2.3: Sternberg Paradigm

Response Times: Only response times of correct responses were used for analysis. A minimum response time cut-off of 200 ms and a maximum response time cut off of 2000 ms was set for all levels using the methods previously described.

There was a tendency for response times to be on average 53 ms quicker on the breakfast trial, though this did not reach statistical significance (main effect of trial, \( t_{(1,28225)} = 2.0, p = 0.051 \)). There was no difference in response times between early and later in the morning (main effect of session time, \( p = 0.782 \)) but as expected, response times were slower with greater memory loads (main effect of memory load, \( t_{(1,28225)} = 17.8, p < 0.001 \)).

On the number level, response times were quicker on the breakfast trial compared to the no breakfast trial. However, on the 3 letter level there was no difference in response times between the breakfast and no breakfast trials, whereas on the 5 letter level response times
were quicker on the no breakfast trial compared to the breakfast trial (trial by load interaction, \( t_{(1,28225)} = 2.6, p = 0.010 \)). However, the pattern of change in response times across the morning was not different between the trials (trial by session time interaction, \( t_{(1,28225)} = 1.8, p = 0.066 \)).

There was however a significant, three-way trial by session time by memory load interaction (\( t_{(1,28225)} = 2.5, p = 0.012 \), figure 4.6). On the least cognitively demanding number level, the improvement in response times across the morning was greatest on the no breakfast trial (figure 4.6a). On the intermediate (3 letter level), the improvement in response times across the morning was similar on the breakfast and no breakfast trials (figure 4.6b). On the most cognitively demanding 5 letter level, response times improved considerably more across the morning on the breakfast trial (figure 4.6c). This reversal of the trial effect on the lowest and highest working memory loads over time causes the three-way interaction.

**Accuracy:** There was no main effect of breakfast (main effect of trial, \( p = 0.643 \)) or the time of the morning (main effect of session time, \( p = 0.139 \)) on accuracy during the Sternberg test. However, there was a significant effect of memory load on accuracy, with students achieving more correct responses on the number level than the three letter level, where in turn they achieved more correct responses than the five letter level (main effect of memory load, \( z_{(1,31089)} = 3.6, p < 0.001 \)).

There was no difference in the pattern of change of accuracy across the morning between the breakfast and no breakfast trials (trial by session time interaction, \( p = 0.997 \)), nor did the memory load influence the effect of breakfast on the accuracy of responses (trial by memory load interaction, \( p = 0.341 \)). Also, there was no difference in accuracy between
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Figure 4.6a: Number level

Figure 4.6b: 3 letter level

Figure 4.6c: 5 letter level

Figure 4.6: Response times across the morning on the breakfast (BR) and no breakfast (NB) trials on each level of the Sternberg paradigm (trial by session time by memory load interaction, p = 0.012)
trials across the morning between the test levels (3-way trial by session time by memory load interaction, p = 0.781).

4.3.3: Capillary Blood Samples

Analysis revealed that blood glucose concentrations were significantly higher on the breakfast trial compared to the no breakfast trial (5.08 vs. 4.17 mmol.l⁻¹ respectively) (main effect of trial, F(1,59) = 57.1, p < 0.001). As expected, blood glucose concentrations were also significantly higher early in the morning when compared to later in the morning (5.01 vs. 4.24 mmol.l⁻¹ respectively) (main effect of session time, F(1,59) = 55.9, p < 0.001). On the breakfast trial, blood glucose concentration was highest immediately following feeding and decreased during the morning. In contrast, on the no breakfast trial, there was also a decrease in blood glucose concentrations across the morning, but at a much slower rate than seen on the breakfast trial (trial by session time interaction, F(1,59) = 17.0, p < 0.001, figure 4.7).

![Figure 4.7: Blood glucose concentration across the morning on the breakfast (BR) and no breakfast (NB) trials. Data are mean ± S.E.M.. (trial by session time interaction, p < 0.001)](image-url)
4.4: Discussion

The main finding of the present study was that breakfast consumption improved the accuracy of responses on the cognitive function tests, particularly on the more cognitively demanding tasks (e.g. Stroop test and the complex level of the visual search test). Breakfast consumption also improved response times on the more complex levels of the Sternberg paradigm, but did not have consistent effects on response times on the other tests conducted. Breakfast consumption also resulted in higher self-reported energy and fullness, lower self-reported tiredness and hunger and as expected, higher blood glucose concentrations.

4.4.1: Visual Search

In the present study, the findings indicate that following breakfast consumption participants achieved a greater proportion of correct responses on the complex level of the visual search test, particularly early in the morning (figure 4.4b). These findings suggest that breakfast consumption is particularly beneficial for the more cognitively demanding task, whereas performance on the more simple task (the baseline level) is similar with or without breakfast consumption (figure 4.4a).

Another study to suggest a beneficial effect of breakfast consumption on visual perception indicates that in 6 to 8 year old boys, accuracy on the Rey complex figure copy and recall test was improved following a ready to eat cereal when compared to breakfast omission, but in 6 to 8 year old girls accuracy was improved following breakfast omission compared to a ready to eat cereal. However, in the 9 to 11 year olds, breakfast consumption improved accuracy in both sexes regardless of composition (i.e. accuracy was improved following both the ready to eat cereal and oatmeal breakfasts compared to the no breakfast
condition) (Mahoney et al, 2005). Overall, the authors concluded that children tended to perform better on a visual perception task following breakfast consumption compared to breakfast omission, but both the age group of the young people and breakfast composition appear to play mediating roles. Interestingly, in accordance with the present study, the effects of breakfast were only evident when looking at the accuracy of visual perception, with no effects on response times on the test of visual perception.

A study conducted in 9 to 12 year old males also reported that there was no effect of breakfast consumption on response times (in accordance with the present study) or accuracy (in contrast to the present study) during the same Rey complex figure copy and recall test (Busch et al, 2002). A potential explanation for this variation in findings could be that whilst the present study and the study of Mahoney et al (2005) compared breakfast consumption and breakfast omission, the study of Busch et al (2002) compared consumption of a confectionary snack and a non-calorie snack (control condition). Furthermore, the Rey complex figure copy and recall test used in the study of Busch et al (2002) was perhaps not cognitively demanding enough for the study population, thus would not elucidate the beneficial effects of breakfast consumption (similar to the baseline level of the visual search test employed in the present study). However, Mahoney et al (2005) tested a younger population (6-11 year olds) and thus the test may have been cognitively demanding enough for these children.

4.4.2: Stroop Test

In the present study accuracy on the Stroop test declined across the morning following breakfast omission but was better maintained across the morning following breakfast consumption (figure 4.5). However, response times on the Stroop test were not affected by
breakfast consumption. To the author’s knowledge, the effects of breakfast consumption and/or omission on adolescents’ performance on the Stroop test have not previously been published. However, the Stroop test was included in the testing battery of a study looking at the effects of the glycaemic load (GL) and glycaemic index (GI) of breakfast in an adolescent population (Micha et al, 2008). Their findings indicated that a high GL and high GI breakfast tended to produce better performance on the Stroop test compared to a low GL and low GI breakfast. It was further suggested that this may be due to a high GL and high GI breakfast resulting in a higher blood glucose concentration and consequently greater activation of the hypothalamic-pituitary-adrenal (HPA) axis, resulting in better performance on the Stroop test (Dye et al, 2000; Micha et al, 2008).

Glucose is a key substrate used by the brain for cognitive activity (Pollitt & Matthews, 1998) and higher blood glucose concentrations increase the delivery of glucose to the brain and as a result, increase frontal lobe functioning (Dye et al, 2000). Due to the key role of the frontal lobe in determining performance on the Stroop test (MacLeod, 1991) it is unsurprising that in the present study accuracy was better maintained following breakfast consumption (and its associated higher blood glucose levels). However, the present study is the first to report the effects of breakfast consumption on performance on the Stroop test in adolescents, with a limited number of other studies focussing on blood glucose concentrations rather than breakfast consumption per se.

4.4.3: Sternberg Paradigm

In the present study, the effect of breakfast consumption on response times on the Sternberg paradigm depended upon the test level (figure 4.6). On the simplest level, response
times showed a greater improvement across the morning on the no breakfast trial, whereas on the more cognitively demanding levels there was a greater improvement in response times across the morning following breakfast consumption. These observations imply that response speed on basic cognitive tasks (i.e. those with a low working memory load) is slow directly after missing breakfast, but can improve over time even without additional meals. In contrast, response speed for demanding cognitive tasks (i.e. those with a high working memory load) is improved to a far greater extent two hours after having breakfast, after which time presumably the meal was digested. These results are consistent with the notion that breakfast consumption is most beneficial for cognitively demanding tasks, particularly later in the morning. In contrast to the other tests employed in the present study, when examining accuracy on the Sternberg paradigm there was no effect of breakfast consumption, with a similar proportion of correct responses on the breakfast and no breakfast trials across the morning.

In accordance with the findings of the present study, several early studies in the area also found there was no effect of breakfast consumption on the accuracy of memory (Dickie & Bender, 1982; Cromer et al, 1990). In contrast, the findings of a more recent study (Widenhorn-Müller et al, 2008) indicated that the accuracy of visuospatial memory was improved following breakfast consumption. However, due to the different components of memory being measured, it is difficult to make comparisons between the present study and those previously conducted in adolescent populations (Dickie & Bender, 1982; Cromer et al, 1990; Widenhorn-Müller et al, 2008).

To the authors’ knowledge, the present study is the first to assess the effects of breakfast consumption on performance of the Sternberg paradigm, thus comparisons with previous studies are difficult. Furthermore, comparisons are made even more difficult due to
the different age groups of the populations tested and the different components of memory measured throughout the literature. Previously, tentative conclusions have been drawn to suggest that breakfast omission adversely affects memory processes in young people, though the evidence in adolescent populations is limited and it is suggested more work should be conducted in this population (Pollitt & Matthews, 1998). The present study partly addresses this void in the literature, with the findings suggesting that breakfast consumption tended to improve the speed of working memory (especially on the more cognitively demanding levels of the Sternberg paradigm later in the morning), but there was no effect on the accuracy of working memory.

**4.4.4: Mood**

The findings of the present study indicate that following breakfast consumption self-report energy and fullness were higher and self-report tiredness and hunger were lower when compared to breakfast omission. A number of studies which have examined the effects of breakfast consumption on cognitive function in young people have also measured the effect on mood. Not only is the effect on mood states interesting in its own right, but it is also suggested that mood can influence cognitive function, thus it should be measured in studies assessing cognitive function. Furthermore, researchers must ensure that the tools used to assess mood are appropriate for use in the study population. For example, the modified version of the ADACL short form used in the present study was found to be suitable for use in an adolescent population.

One study assessing mood and cognitive function in an adolescent population assessed the effects of breakfast consumption on information uptake, positive affect, negative
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affect, alertness and arousal in 13 to 20 year olds (Widenhorn-Müller et al, 2008). The findings indicate that following breakfast consumption, the overall study population reported greater positive affect, information uptake and alertness, along with lower negative affect, compared to the no breakfast condition. Similarly, it has been reported that breakfast consumption produced greater self-rated alertness and contentment compared to breakfast omission in 9 to 16 year olds (Wesnes et al, 2003). These findings are consistent with those of the present study, which also showed increased energy and decreased tiredness following breakfast consumption, indicative of a more positive mood state.

Comparisons between the present study and those described above should be made cautiously for a number of reasons. First, the above studies have all used different methods of assessing mood and are therefore assessing different dimensions of mood. Furthermore, the above studies have tended to use mood questionnaires designed for use in adults, thus their suitability for use in young people must be questioned. Interestingly, the studies where a consistent effect of breakfast consumption on mood has been demonstrated have been conducted in adolescents, rather than younger children. This could be explained in two ways; firstly it could be that breakfast consumption does not affect mood in younger children but does so in adolescents, or it could be that younger children are unable to understand the construct of mood and/or use the mood questionnaires accurately because they were designed to be used in adults, highlighting the need for mood questionnaires to be appropriate for the study population.
4.4.5: Summary and Future Research Directions

The main finding of the present study was that breakfast consumption improved the accuracy of responses on the visual search and Stroop tests. Breakfast consumption also improved response times on the more complex levels of the Sternberg paradigm, but did not have consistent effects on response times on the other tests conducted. Overall, it would appear that breakfast consumption was particularly beneficial on the more cognitively demanding tasks, whereas the simpler tasks could be performed to a similar level following breakfast omission.

The present study is unique in its findings for a number of reasons. First, it employed an adolescent population, whereas much of the literature to date has used either younger children or an adult population. Second, the number of participants is larger than many other studies in the literature, particularly those studying adolescents. Furthermore, the present study provided participants with breakfast ad libitum, allowing for a breakfast meal similar to habitual breakfast intake. Many other studies have used a fixed breakfast, possibly accounting for a lack of an effect of breakfast on cognitive function in such studies. Finally, the present study also measured blood glucose concentrations, providing a biochemical marker that is not available in many of the studies in the literature to date, allowing an insight into the potential mechanisms for the effect of breakfast consumption on cognitive function in adolescents.

In summary, the findings of the present study suggest that breakfast consumption does improve cognitive function in an adolescent population. Therefore, because of this improvement in cognitive function and the other suggested health benefits of breakfast consumption (Pearson et al, 2009) it is a practice that should be promoted in adolescent populations. However, further work is required to examine the optimal composition of breakfast (with particular interest in the glycaemic index), the optimal timing of breakfast,
and to suggest potential mechanisms for an effect of breakfast consumption on cognitive function.
Chapter V

Breakfast Glycaemic Index and Cognitive Function in Adolescent School Children

5.1: Introduction

Breakfast consumption, as opposed to breakfast omission, has a positive impact on cognitive function in adults (Smith et al, 1994; Benton et al, 2001), children (Hoyland et al, 2009) and adolescents (Widenhorn-Müller et al, 2008; chapter IV). In adults, the effects on cognition of breakfasts differing in macronutrient content (Fischer et al, 2001), glycaemic load (Gilsenan et al, 2009) and glycaemic index (GI) (Benton et al, 2003; Benton & Nabb, 2004; Nilsson et al, 2009) have also been examined, with evidence suggesting that low GI foods are beneficial for some aspects of adults’ cognitive function, including working memory (Benton et al, 2003; Nilsson et al, 2009) and attention (Nilsson et al, 2009).

Fewer studies have examined the effect of the GI of breakfast on cognitive function of young people and adolescents, and the findings have been equivocal (Hoyland et al, 2009). It has been suggested that adolescent populations are particularly important to study in this field as whilst going through puberty, adolescents undergo rapid growth and changes in metabolism and thus their responses may be different to those of younger children and adults (Cromer et al, 1990; Kanarek, 1997). Furthermore, the academic work completed by adolescents is of a greater complexity than in younger children, compounded by ongoing assessments at school. Therefore, the additional academic stress could exacerbate any nutritional effects on cognitive function (Cromer et al, 1990).
However, only three studies to date have examined the effect of the GI of breakfast on cognitive function in an adolescent population (Wesnes et al, 2003; Smith & Foster, 2008; Micha et al, 2010). One of these studies has shown that a high GI glucose drink and breakfast omission resulted in a decline in attention and memory during the school morning, but this decline was reduced following the consumption of low GI breakfast cereals (Wesnes et al, 2003). However, nutritional information on the breakfasts was not provided and there was a wide age range of participants (9 to 16 year olds), not all of whom were adolescents. In contrast, another study has shown that 90 min after breakfast consumption, 14-17 year olds were able to remember more items following a high GI compared to a low GI breakfast (Smith & Foster, 2008). It was suggested that this enhanced memory could be the result of higher blood glucose concentrations following the high GI breakfast, which would be beneficial under the conditions of divided attention. However, there were no significant differences in blood glucose concentration between the trials and only one element of cognitive function was assessed, namely verbal episodic memory. In the one further study it was reported that performance on a speed of information processing task and a serial sevens task was enhanced following a low GI breakfast, whereas a high GI breakfast was beneficial for immediate word recall (Micha et al, 2010). However, the breakfasts provided were not matched on key variables, such as energy and carbohydrate content.

Thus, the findings are equivocal regarding the effects of the GI of breakfast on cognitive function in adolescents, with the possibility that the effects of high and low GI breakfasts vary for different elements of cognitive function. Therefore, the aim of the present study was to conduct a randomised control trial, using a crossover design, to assess the effects of a high GI breakfast, a low GI breakfast and breakfast omission on cognitive function in adolescent schoolchildren. The study employed a battery of computer tests to
assess various elements of cognitive function. Furthermore, blood glucose and plasma insulin concentrations were measured to allow a possible insight into the mechanisms for any effects of the GI of breakfast on cognitive function in adolescent school children.

5.2: Methodology

5.2.1: Participant Characteristics

Fifty-two participants aged 12 to 14 years were recruited to participate in the study. However, eleven participants were removed from the study because they were absent from school for one or more of the experimental trials (n = 9), or did not follow the dietary requirements (n = 2). Therefore, forty-one participants completed the study. During familiarisation, simple measures of height, body mass and waist circumference were taken using the methods described in section 3.3. For descriptive purposes, the anthropometric characteristics of the participants are provided in table 5.1.

<table>
<thead>
<tr>
<th></th>
<th>Age [yrs]</th>
<th>Height [cm]</th>
<th>Body Mass [kg]</th>
<th>BMI [kg.m$^{-2}$]</th>
<th>Waist Circumference [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>12.4±0.5</td>
<td>158.7±7.9</td>
<td>52.0±10.6</td>
<td>20.2±3.5</td>
<td>70.5±8.0</td>
</tr>
<tr>
<td>Female</td>
<td>12.6±0.6</td>
<td>157.3±7.4</td>
<td>51.2±10.9</td>
<td>20.8±3.2</td>
<td>68.3±7.5</td>
</tr>
<tr>
<td>Overall</td>
<td>12.5±0.6</td>
<td>157.9±7.5</td>
<td>51.6±10.6</td>
<td>20.5±3.3</td>
<td>69.3±7.7</td>
</tr>
</tbody>
</table>

All values are mean ± standard deviation.

5.2.2: Study Design

The study was approved by Loughborough University Ethical Advisory Committee. Consent was gained from participants using the methods described in section 3.2. In brief, a
written parental informed consent form and health screen questionnaire was completed by participants’ parents or guardians prior to participation in the study.

Each participant undertook a familiarisation session followed by three experimental trials. During familiarisation, which preceded the first experimental trial by seven days, the protocol of the study was explained to participants and they were provided with an opportunity to familiarise themselves with the methods involved. Participants were allowed to repeat the cognitive function tests until they felt comfortable with them, to negate any potential learning effects.

The study employed a randomised crossover design and was order balanced, with participants blinded against trial condition until arrival at school on each day of testing. The experimental trials consisted of a high glycaemic index breakfast (high GI) trial, a low glycaemic index breakfast (low GI) trial and breakfast omission trial (where breakfast was provided upon completion of the protocol). Therefore, participants acted as their own controls and the effects of the different breakfast conditions can be assessed as within-subject factors. Trials were scheduled seven days apart and participants reported to school at the normal time. The experimental protocol is shown in figure 5.1.

![Figure 5.1: Experimental Protocol](image)

**Figure 5.1:** Experimental Protocol
Upon arrival at school participants rested in a seated position for 10 min and then a capillary blood sample was taken. The protocol commenced as participants began breakfast on the high and low GI trials, whereas on the breakfast omission trial the protocol commenced after the resting capillary blood sample had been collected. On the high and low GI trials, participants were given 15 min to consume breakfast, whereas on the breakfast omission trial participants rested for 15 min. Capillary blood samples and the cognitive function tests were completed during the subsequent monitoring period. A 120 min monitoring period was selected based upon recommendations which suggest that this is a sufficient period of time to elicit the different glycaemic responses between the meals (Brouns et al, 2005). This is also the period of time after which the effects of breakfast consumption on cognitive function become apparent in chapter IV and throughout the literature (Wesnes et al, 2003; Micha et al, 2010; Benton et al, 2007).

5.2.3: Dietary Control

Participants were asked to consume a meal of their choice the evening before their first experimental trial and then to repeat this meal for each of the subsequent trials. Participants fasted from 10 pm the evening before each experimental trial. In order to maintain euhydration, participants were allowed to drink water ad libitum during this time. In addition, participants avoided any unusually vigorous exercise for 24 h prior to each experimental trial. Prior to each main trial a telephone call was made to participants to remind them of this information. On the day of each experimental trial, participants were asked to indicate if they had followed the above requirements when they arrived at school.
5.2.4: Capillary Blood Sampling

Capillary blood samples were taken at baseline and 15, 30, 60 and 120 min after breakfast consumption on each trial using the methods described in detail in section 3.6.1. The variables of interest were blood glucose and plasma insulin concentrations, determined using the methods described in section 3.6.2. Incremental area under the curve (IAUC) for blood glucose and plasma insulin was also calculated, using the methods described by Wolever & Jenkins (1986).

5.2.5: Mood Questionnaire

The modified version of the ‘Activation-Deactivation Check List’ (ADACL), as described in section 3.5, was completed by participants at baseline and 30, 60 and 120 min following breakfast consumption. The ADACL provided a measure of participants’ self-report energy, tiredness, tension and calmness. In addition, three visual analogue (VAS) scales were used to provide a measure of participants’ hunger, fullness and concentration (see section 3.5). Both the ADACL and VAS scales allow comparisons between time points.

5.2.6: Cognitive Function Tests

The battery of cognitive function tests was administered via a laptop computer and was completed 30 and 120 min following breakfast consumption. The battery of tests for this study consisted of the visual search test, the Stroop test, the Sternberg paradigm and the Flanker task, which are described in detail in section 3.4.
**5.2.7: Breakfast**

Breakfast was provided after the resting measures had been taken and participants had 15 min to consume breakfast. The high and low GI breakfasts both contained 1.5 g.kg\(^{-1}\) body mass available carbohydrate and were matched for energy, protein and fat content, as described in section 3.7.2. The breakfast composition for a 50 kg participant is shown in table 3.2.

**5.2.8: Statistical Analysis**

The mood, blood glucose and plasma insulin data were analysed using SPSS (Version 16, SPSS Inc., Chicago, Il, USA) via two-way Analysis of Variance (ANOVA) for repeated measures (trial by session time). The main effects of trial and session time were also investigated. Data are reported as mean ± S.E.M..

The cognitive function data were analysed using R (www.r-project.org, version 2.9.1). Linear mixed effects models were used to analyse the data, corrected for repeated measures with a random effect for each participant. Response time analyses were performed using the nlme package and accuracy analyses were performed with the lme4 package with a binomial outcome data distribution to properly account for the binomial (correct/incorrect) accuracy scores. All analyses were conducted using a three-way trial by session time by test level interaction. Where the three-way interaction was not significant, a two-way trial by session time interaction was conducted, as well as the main effects of trial. For all analysis, significance was set as p < 0.05.
5.3: Results

5.3.1: Mood

5.3.1.1: Energy

Analysis revealed a main effect of trial ($F_{(2,80)} = 5.7$, $p = 0.008$), with self-report energy higher on the high GI trial compared to the breakfast omission trial (16.6 vs. 14.8 respectively, $p = 0.023$) and tending to be higher on the low GI trial compared to the breakfast omission trial, though this did not reach statistical significance (16.3 vs. 14.8 respectively, $p = 0.065$). However, there was no difference between self-report energy on the high and low GI trials ($p = 1.000$). There was also a significant effect of time on self-report energy, with participants reporting feeling more energetic later in the morning ($F_{(3,120)} = 10.6$, $p < 0.001$). Self-report energy increased following both the high and low GI breakfasts, whereas it remained at a similar level following breakfast omission, however the trial by time interaction did not reach statistical significance ($F_{(6,240)} = 2.0$, $p = 0.098$, figure 5.2).

![Figure 5.2: Self-report energy across the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± S.E.M.](image_url)

(trial by time interaction, $p = 0.098$; * HGI & LGI > NBF, $p < 0.05$)
### 5.3.1.2: Tiredness

There was no difference in self-report tiredness between the trials (main effect of trial, \( p = 0.100 \)). However, self-report tiredness decreased across the morning on all trials (main effect of time, \( F_{(3,120)} = 9.8, p < 0.001 \)), but the decrease was greatest on the high GI trial, then the low GI trial whereas self-report tiredness remained higher on the breakfast omission trial (trial by time interaction, \( F_{(6,240)} = 2.7, p = 0.033 \), figure 5.3).

![Figure 5.3](image.png)

**Figure 5.3:** Self-report tiredness across the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± S.E.M..

(trial by time interaction, \( p = 0.033 \); * NBF > HGI, + LGI > HGI, all \( p < 0.05 \))

### 5.3.1.3: Tension

There was no difference in self-report tension between the trials (main effect of trial, \( p = 0.587 \)). However, self-report tension decreased across the morning (main effect of time,
$F_{(3,120)} = 6.4, p = 0.003$, though this decrease was not different between trials (trial by time interaction, $p = 0.118$).

5.3.1.4: Calmness

There was no difference in self-report calmness between the trials (main effect of trial, $p = 0.589$). However, calmness did decrease across the morning (main effect of time, $F_{(3,120)} = 6.9, p = 0.001$), though as with tension this decrease was not different between trials (trial by time interaction, $p = 0.612$).

5.3.1.5: Hunger

Analysis revealed a main effect of trial on self-report hunger ($F_{(2,80)} = 102.8, p < 0.001$), with further analysis revealing that hunger was lower following both the high GI (4.0) and low GI (4.2) breakfasts when compared to breakfast omission (8.2, both $p < 0.001$). However, there was no difference in self-report hunger between the high and low GI trials ($p = 1.000$). As expected, self-report hunger also decreased across the morning (main effect of time, $F_{(3,120)} = 68.3, p < 0.001$), though upon further analysis self-report hunger decreased by a similar magnitude following the high and low GI breakfasts, but increased slightly across the morning on the breakfast omission trial (trial by time interaction, $F_{(6,240)} = 36.2, p < 0.001$, figure 5.4).
Figure 5.4: Self-report hunger across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± S.E.M..

(trial by time interaction, p < 0.001; * NBF > HGI & LGI, p < 0.05)

5.3.1.6: Fullness

As expected, the results for self-report fullness show the opposite effects of those for self-report hunger, with analysis revealing a significant main effect of trial ($F_{(2,78)} = 98.1$, $p < 0.001$), with further analysis revealing that fullness was higher following both the high GI (6.0) and low GI (5.7) breakfasts when compared to breakfast omission (1.8, both $p < 0.001$). However, there was no difference in self-report fullness between the high and low GI trials ($p = 0.800$). As expected, self-report fullness increased across the morning (main effect of time, $F_{(3,117)} = 92.9$, $p < 0.001$), though upon further analysis, as expected, fullness increased by a similar magnitude following the consumption of both the high and low GI breakfasts, whereas fullness remained at the baseline level across the morning on the breakfast omission trial (trial by time interaction, $F_{(6,234)} = 42.9$, $p < 0.001$, figure 5.5).
Figure 5.5: Self-report fullness across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± S.E.M..

(trial by time interaction, p < 0.001; * HGI & LGI > NBF, p < 0.05)

5.3.1.7: Concentration

Analysis revealed a significant main effect of trial on self-report concentration ($F_{(2,78)} = 41.2, p < 0.001$), with further analysis revealing that self-report concentration was higher on both the high GI (6.7) and low GI (6.5) trials compared to the breakfast omission trial (4.4, both $p < 0.001$). However, there was no difference in self-report concentration between the high and low GI trials ($p = 0.866$). Self-report concentration increased across the morning (main effect of time, $F_{(3,117)} = 14.5, p < 0.001$), though upon further analysis it was revealed that self-report concentration increased following consumption of both the high and low GI breakfasts, whereas it decreased slightly across the morning on the breakfast omission trial (trial by time interaction, $F_{(6,234)} = 12.1, p < 0.001$, figure 5.6).
Figure 5.6: Self-report concentration across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± S.E.M. (trial by time interaction, p < 0.001; * HGI & LGI > NBF, p < 0.05)

5.3.2: Cognitive Function Tests

For all timed cognitive tests the response times were first log-transformed to normalise the distributions, which exhibited the right-hand skew typical of human response times. Minimum response time cut-offs were then chosen based on what may reasonably be expected to be the fastest possible human response to the given stimuli (200 – 300 ms, depending on task complexity) to exclude unreasonably fast responses, which relate to response key presses before stimuli have even been perceived. Maximum response time cut-offs were determined so as to remove unreasonably long right-hand tails for a normal distribution, corresponding to five standard deviations individually for each test and test level.
5.3.2.1: Visual Search Test

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, responses faster than 300 ms for both test levels and slower than 1500 ms for the baseline level and 10000 ms for the complex level were removed.

Overall, response times were quicker following the low GI breakfast and breakfast omission, when compared to following the high GI breakfast (main effects of trial: LGI vs. HGI: $t_{(1, 10079)} = 4.7, p < 0.001$; NBF vs. HGI: $t_{(1,10079)} = 3.3, p = 0.001$). Response times were similar across the morning on all three trials on the baseline level of the visual search test (figure 5.7a). However, on the complex level (figure 5.7b), response times were quicker 120 min following breakfast consumption following both a low GI breakfast and breakfast omission, when compared to following a high GI breakfast (trial by session time by test level interactions: LGI vs. HGI: $t_{(1,10072)} = 2.2, p = 0.025$; NBF vs. HGI: $t_{(1,10072)} = 2.0, p = 0.047$, figure 5.7).

Accuracy: Overall, students achieved a greater proportion of correct responses following both the low GI breakfast and breakfast omission, when compared to following the high GI breakfast (main effects of trial: LGI vs. HGI: $z_{(1,10972)} = 3.2, p = 0.001$; NBF vs. HGI: $z_{(1,10972)} = 3.5, p < 0.001$). However, there was no difference in the overall proportion of correct responses between the low GI and breakfast omission trials (main effect of trial, $p = 0.761$).

On the baseline level, students achieved a greater percentage of correct responses later in the morning following breakfast omission, whereas they achieved less correct responses later in the morning following the low GI breakfast (figure 5.8a). However, on the more cognitively demanding complex level, students achieved more correct responses later in the
Figure 5.7: Response times across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the baseline (figure 5.7a) and complex (figure 5.7b) levels of the visual search test.

(LGI vs. HGI: trial by session time by test level interaction, p = 0.025; NBF vs. HGI: trial by session time by test level interaction, p = 0.047)
morning following a low GI breakfast, whereas accuracy decreased across the morning on the breakfast omission trial (figure 5.8b). These effects produce a significant three-way interaction (trial by session time by test level interaction, $z_{(1,7263)} = 2.1$, $p = 0.032$, figure 5.8). There were no other significant interactions between the different conditions and the testing time and test level on the visual search test (all $p > 0.05$).

5.3.2.2: Stroop Test

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described responses faster than 250 ms for both test levels and slower than 2500 ms for the baseline level and 4000 ms for the complex level were removed.

Response times were quicker following the high GI breakfast when compared to the low GI breakfast (main effect of trial, $t_{(1,13537)} = 2.1$, $p = 0.031$). Response times following the high GI breakfast tended to be quicker 120 min following breakfast consumption when compared to breakfast omission, an effect specific to the complex level, but this did not reach statistical significance (trial by session time by test level interaction, $t_{(1,13530)} = 1.8$, $p = 0.079$, figure 5.9). Furthermore, response times following the low GI breakfast were quicker 120 min following breakfast consumption when compared to breakfast omission and again this effect was specific to the complex level (trial by session time by test level interaction, $t_{(1,9019)} = 2.6$, $p = 0.009$, figure 5.9). However, the pattern of change in response times across the morning between the high and low GI trials was not different (trial by session time by test level interaction and trial by session time interaction, both $p > 0.05$).
Figure 5.8a: Baseline level

Figure 5.8b: Complex level

Figure 5.8: Accuracy across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the baseline (figure 3a) and complex (figure 3b) levels of the visual search test

(LGI vs. NBF: trial by session time by test level interaction, p = 0.032)
Figure 5.9: Response times across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the baseline (figure 5.9a) and complex (figure 5.9b) levels of the Stroop test.

(HGI vs. NBF: trial by session time by test level interaction, p = 0.079; LGI vs. NBF: trial by session time by test level interaction, p = 0.009)
Accuracy: Students achieved more correct responses following the low GI breakfast compared to following both the high GI breakfast (main effect of trial, $z_{(1,14820)} = 2.1, p = 0.039$) and breakfast omission (main effect of trial, $z_{(1,14820)} = 3.6, p < 0.001$). However, there was no significant difference in the proportion of correct responses between the high GI and breakfast omission trials (main effect of trial, $p = 0.150$).

On the high GI trial, there was a greater decrease in accuracy across the morning when compared to the low GI trial (trial by session time interaction, $z_{(1,14820)} = 2.1, p = 0.033$, figure 5.10). However, this effect was not specific to the test level (trial by session time by test level interaction, $p = 0.121$). There were no other significant interactions between the different conditions and the testing time and/or the test level (all $p > 0.05$).

![Figure 5.10: Accuracy across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the Stroop test](image)

(LGI vs. HGI: trial by session time interaction, $p = 0.033$)
5.3.2.3: Sternberg Paradigm

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, responses faster than 200 ms and slower than 2000 ms for all test levels were removed.

Overall, participants responded quicker following breakfast omission compared to following both the high GI breakfast (main effect of trial, \( t_{(1,17468)} = 3.6, p < 0.001 \)) and the low GI breakfast (main effect of trial, \( t_{(1,17468)} = 2.5, p = 0.011 \)). However, whilst response times remained similar across the morning following the high GI breakfast, there was a greater improvement in response times across the morning following the low GI breakfast (trial by session time interaction, \( t_{(1,17438)} = 2.5, p = 0.013 \), figure 5.11).

**Figure 5.11:** Response times across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the Sternberg paradigm

\( (LGI \text{ vs. } HGI: \text{trial by session time interaction, } p = 0.013) \)
Accuracy: Overall, participants achieved a greater proportion of correct responses following the low GI breakfast when compared to breakfast omission (main effect of trial, \( z_{(1,19520)} = 2.1, p = 0.036 \)), but there was no difference between the low GI and high GI or the high GI and breakfast omission trials (main effects of trial, \( p = 0.118 \) and \( p = 0.586 \) respectively).

Whilst accuracy was similar across the morning between the trials on the easier levels (figures 5.12a and 5.12b), on the more complex (five letter) level of the Sternberg paradigm (figure 5.12c) accuracy was better maintained across the morning following the low GI breakfast when compared to the high GI breakfast (trial by session time by test level interaction, \( z_{(1,19520)} = 3.1, p = 0.002 \), figure 5.12). There was also a tendency for accuracy to be better maintained across the morning following the low GI breakfast when compared to the breakfast omission trial, again this effect was only evident on the more complex levels (trial by session time by test level interaction, \( z_{(1,19520)} = 2.0, p = 0.051 \), figure 5.12).

5.3.2.4: Flanker Task

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, responses faster than 100 ms and slower than 2500 ms were removed. Overall, response times were similar between the trials (main effects of trial: high GI vs. low GI, \( p = 0.497 \); high GI vs. breakfast omission, \( p = 0.909 \); low GI vs. breakfast omission, \( p = 0.634 \)). However, there was a greater improvement in response times across the morning following the low GI breakfast, compared to breakfast omission (trial by session time interaction, \( t_{(1,13630)} = 2.0, p = 0.045 \), figure 5.13). Apart from this interaction, response times across the morning were similar between the trials on both levels (all interactions, \( p > 0.05 \)).
Figure 5.12: Accuracy across the morning on high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the number (figure 5.12a), three-letter (figure 5.12b) and five-letter (figure 5.12c) levels of the Sternberg paradigm

(LGI vs. HGI: trial by session time by test level interaction, p = 0.002;
LGI vs. NBF: trial by session time by test level interaction, p = 0051)
Figure 5.13: Response times across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the Flanker task

(LGI vs. NBF: trial by session time interaction, p = 0.045)

Accuracy: Overall, there was no significant difference in the proportion of correct responses between the trials (main effects of trial: high GI vs. low GI, p = 0.931; high GI vs. breakfast omission, p = 0.859; low GI vs. breakfast omission, p = 0.805). However, on the incongruent (more complex) level, accuracy was better maintained across the morning following the low GI breakfast compared to the high GI breakfast (trial by session time by test level interaction, \( z_{(1,14700)} = 2.5, p = 0.014, \) figure 5.14) and breakfast omission (trial by session time by test level interaction, \( z_{(1,14700)} = 0.001, \) figure 5.14).
Figure 5.14a: Congruent level

Figure 5.14b: Incongruent level

Figure 5.14: Accuracy across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the congruent (figure 5.14a) and incongruent (figure 5.14b) levels of the Flanker task

(LGI vs. HGI: trial by session time by test level interaction, p = 0.014; LGI vs. NBF: trial by session time by test level interaction, p = 0.001)
5.3.3: Capillary Blood Samples

5.3.3.1: Blood Glucose Concentration

Blood glucose concentrations and the pattern of response across the morning were different between the trials (main effect of trial, time and trial by time interaction, all $p < 0.001$). However, because the differences between breakfast omission and breakfast consumption were expected, the following results consider only the high GI and low GI trials, with the breakfast omission trial shown on the figures only for illustration purposes.

Blood glucose concentration was significantly higher on the high GI trial, compared to the low GI trial (main effect of trial, $F_{(1,39)} = 44.4, p < 0.001$). As expected, blood glucose concentrations increased after both the high and low GI breakfasts, peaking at 30 min, before returning towards resting concentrations (main effect of time, $F_{(4,156)} = 138.3, P < 0.001$). However, blood glucose concentrations reached a higher peak at 30 min on the high GI trial compared to the low GI trial (7.01 vs. 6.46 mmol.l$^{-1}$ respectively, $p < 0.001$) and remained higher 60 and 120 min following breakfast (60 min: 5.23 vs. 4.71 mmol.l$^{-1}$; 120 min: 5.01 vs. 4.69 mmol.l$^{-1}$, both $p < 0.001$). This produced a significant interaction between trial and time (trial by time interaction, $F_{(4,156)} = 5.9, p < 0.001$, figure 5.15). Furthermore, blood glucose incremental area under the curve (IAUC) was also greater following the high GI breakfast compared to following the low GI breakfast (116.6 vs. 80.9 mmol.l$^{-1}$.120 min$^{-1}$ respectively, $p < 0.001$).
Figure 5.15: Blood glucose concentration across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± S.E.M..

(LGI vs. HGI: trial by session time interaction, p < 0.001; * HGI & LGI > NBF, all p < 0.05; + HGI > LGI, all p < 0.05)

5.3.3.2: Plasma Insulin Concentration

Plasma insulin concentrations and the pattern of response across the morning were different between the trials (main effect of trial, time and a trial by time interaction, all p < 0.001). However, because the differences between breakfast omission and breakfast consumption were expected, the following results consider only the high GI and low GI trials, with the breakfast omission trial shown on the figures only for illustration purposes.

Plasma insulin concentration was significantly higher on the high GI trial, compared to the low GI trial (main effect of trial, $F_{(1,40)} = 4.3$, p = 0.045). As expected, plasma insulin concentrations increased after both the high and low GI breakfasts, peaking at 30 min before returning towards resting concentrations (main effect of time, $F_{(4,160)} = 68.1$, p < 0.001).
However, there was no difference in the pattern of change in plasma insulin concentration across the morning between the high and low GI trials (trial by time interaction, $F_{(4,160)} = 0.5$, $p = 0.507$, figure 5.16), nor was there a difference in plasma insulin IAUC following the high and low GI breakfasts (36590 vs. 31651 pmol.l$^{-1}$.120 min$^{-1}$ respectively, $p = 0.063$).

**Figure 5.16:** Plasma insulin concentration across the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± S.E.M..

(LGI vs. HGI: trial by time interaction, $p = 0.507$; * HGI & LGI > NBF, $p < 0.05$; + HGI > LGI, $p < 0.05$)

### 5.4: Discussion

The main finding of the present study is that a low glycaemic index (GI) breakfast enhanced cognitive function in adolescents, when compared to both a high GI breakfast and breakfast omission. Across all four cognitive function tests (visual search test, Stroop test, Sternberg paradigm and Flanker task), a low GI breakfast enhanced both response times and
accuracy later in the morning when compared to a high GI breakfast, breakfast omission, or both, particularly on the more cognitively demanding levels of the tests employed. Ingestion of the low GI breakfast also resulted in a lower peak blood glucose concentration when compared to a high GI breakfast, produced a smaller overall glycaemic response and tended to produce a smaller overall insulinaemic response.

5.4.1: Visual Search Test

Response times on the complex level visual search test improved across the morning following a low GI breakfast and breakfast omission, whereas they increased across the morning following a high GI breakfast (figure 5.7b). Accuracy on the complex level also increased across the morning following a low GI breakfast, whereas it decreased across the morning following breakfast omission (figure 5.8b). It is also important to note that following a high GI breakfast, participants were overall slower and less accurate, than following both the low GI breakfast and breakfast omission.

Another study to assess the effects of breakfast GI on visual perception, as assessed by the visual search test, examined the effects of a high GI breakfast, a low GI breakfast and breakfast omission on performance of the Rey complex figure copy and recall test in 6-8 and 9-11 year olds (Mahoney et al, 2005). In contrast to the findings of the present study, they found no effect of the breakfast condition on response times (Mahoney et al, 2005). However, in the 6-8 year old males, the accuracy of visual perception was greater following a high GI breakfast when compared to breakfast omission, whereas in the 6-8 year old females, accuracy was greater following breakfast omission compared to a high GI breakfast (Mahoney et al, 2005). Furthermore, in the 9-11 year olds, both a high and low GI breakfast
enhanced accuracy when compared to breakfast omission (Mahoney et al, 2005). The findings of the present study, suggest, in addition to a low GI breakfast being the most beneficial for performance of the visual search test, that both response times and accuracy following a high GI breakfast were worse than following the low GI breakfast and breakfast omission.

Overall, it appears that both the age and gender of the participants will affect the influence of breakfast GI on visual perception. The present study is the first to assess this effect in adolescents, with earlier studies focussing on younger children (Mahoney et al, 2005), possibly accounting for the variation in findings. However, the present study adds to the existing literature by demonstrating that in adolescents, both response times and accuracy on the visual search test are enhanced following a low GI breakfast, when compared to a high GI breakfast, breakfast omission, or both. In addition, the results demonstrate that overall a high GI breakfast appears to be detrimental to adolescents’ performance on the visual search test.

5.4.2: Stroop Test

Response times on the Stroop test were quicker overall on the high GI trial, when compared to the low GI trial. Furthermore, on the incongruent (more complex) level of the Stroop test, there was a greater improvement in response times across the morning following a low GI breakfast when compared to breakfast omission (figure 5.9b). Accuracy was also better maintained across the morning following a low GI breakfast when compared to a high GI breakfast (figure 5.10).
Another study to examine the effects of the GI of breakfast on performance on the Stroop test reports that a high GI breakfast was more beneficial than a low GI breakfast, but only in the group who had consumed a high glycaemic load (GL) breakfast (Micha et al., 2008). It has also been reported that neither the GI nor GL of breakfast affects adolescents’ performance on the Stroop test (Micha et al., 2010). However, the earlier studies suffered from a number of methodological weaknesses, including: providing high and low GL meals that were not matched for energy content, not reporting whether response times and/or accuracy were assessed on the Stroop test and furthermore, not employing a crossover design, with participants consuming only the high or low GL breakfasts (Micha et al., 2008; Micha et al., 2010). In comparison, in the present study participants performed all trials in a randomised crossover design and the breakfasts were matched on key variables such as energy and carbohydrate content.

It has previously been suggested that higher blood glucose concentrations are associated with better performance on the Stroop test (Dye et al., 2000). However, studies from which this conclusion was drawn focused on a nutritional intervention (e.g. breakfast or lunch provision) versus continued fasting (e.g. Smith et al., 1994). Similarly, in chapter IV the findings indicate that breakfast consumption (which was associated with higher blood glucose concentrations) improved performance on the Stroop test compared to breakfast omission. However, the present study compares two nutritional interventions (high and low GI breakfasts) with breakfast omission, extending the previous work that examined nutritional interventions versus fasting.

Thus, while the enhanced performance following both the high and low GI breakfasts, compared to following breakfast omission, may be mediated by the higher blood glucose concentrations (Dye et al., 2000), when comparing the high and low GI trials it seems that the
higher blood glucose concentrations enhance response times, but they are to the detriment of accuracy. Alternatively, blood glucose concentrations (within the postprandial ranges following the high and low GI breakfasts) may not be the only determinant of performance on the Stroop test, and other factors such as improved insulin sensitivity following a low GI breakfast (Schulze et al, 2004) may also play a role in determining performance. However, the present study does not allow us to provide details of the mechanistic pathways determining cognitive performance, rather it only allows us to speculate on such mechanisms.

5.4.3: Sternberg Paradigm

There was a greater improvement in response times across the morning on the Sternberg paradigm, a test of working memory, following a low GI breakfast compared to a high GI breakfast (figure 5.11). Furthermore, accuracy was better maintained across the morning following a low GI breakfast compared to following both the high GI breakfast and breakfast omission trials, but this was only evident on the more complex level (figure 5.12c).

The findings of the present study are consistent with an earlier study in 9 to 16 year olds which showed a greater improvement in response times across the morning following a low GI breakfast, compared to both a high GI breakfast and breakfast omission, but in the earlier study the accuracy of working memory was not investigated (Wesnes et al, 2003). The accuracy of working memory has been examined previously in children, with 9 to 11 year old females showing an enhanced accuracy following a low GI breakfast as opposed to a high GI breakfast (Mahoney et al, 2005). However, there were no effects of the different breakfasts in the 9 to 11 year old males or in 6 to 8 year old males or females (Mahoney et al, 2005). Thus,
the present study is the first to examine the effects of the GI of breakfast on both the speed and accuracy of working memory in an adolescent population.

It has been previously suggested that the improvement in working memory following a low GI breakfast could be due to better maintenance of blood glucose concentrations after a ‘simulated’ low GI breakfast (Nilsson et al, 2009). However, in the present study, following the ‘real-life’ low GI breakfast, blood glucose concentrations were lower than following the high GI breakfast, thus contradicting the suggestion that maintenance of higher blood glucose concentrations within normal postprandial ranges is a key determinant of working memory performance.

**5.4.4: Flanker Task**

There was a greater improvement in response times across the morning on the Flanker task, which is a test of selective attention, following a low GI breakfast when compared to breakfast omission (figure 5.13). Furthermore, accuracy on the incongruent (more difficult) level was better maintained across the morning following a low GI breakfast when compared to both the high GI breakfast and breakfast omission (figure 5.14b).

The improvement in accuracy on the Flanker task across the morning following the low GI breakfast is consistent with findings based on classroom observations in 6 to 7 year olds who spent more time on task and demonstrated fewer lapses in attention following a low GI breakfast compared to a high GI breakfast (Benton et al, 2007). Furthermore, in 9 to 16 year olds completing an attentional task as part of the Cognitive Drug Research battery of cognitive tests, the accuracy of attention declined across the morning following a high GI breakfast, but accuracy was better maintained following a low GI breakfast (Wesnes et al,
2003). These findings are in line with those of the present study, but the present study extends findings by using a more widely used test of attention (Flanker task) and focussing on adolescence, a time during which the frontal lobes thought to govern executive functions have been found to undergo a final bout of development (Giedd et al, 1999), whereas earlier studies focused on young people in general.

5.4.5: Glycaemic and Insulinaemic Responses

The glycaemic and insulinaemic responses to meals of differing GI have not been previously reported in adolescent populations. In the present study, adolescents exhibited a larger overall glycaemic response following a high GI breakfast when compared to the low GI breakfast (as determined by IAUC). These findings are consistent with those in adult populations (Wolever & Bolognesi, 1996). It has also been suggested that high GI foods result in a higher insulinaemic response in adults (Wolever & Bolognesi, 1996). However in the adolescents tested in the present study, there was no difference in the overall insulinaemic response following the high GI compared to the low GI breakfast (as determined by IAUC). One potential explanation for the similar insulinaemic response to the high and low GI trials is the matched milk content of the breakfasts, because of the well documented insulinotrophic effect of milk (Liljeberg & Björk, 2001). Therefore, the expected differences in insulinaemia (based on findings in adults) could have been masked by the matched milk content of the meals.
5.4.6: Summary and Future Research Directions

The main finding of the present study is that across a range of cognitive function tests, including the domains of visual perception, working memory and attention, in adolescents a low GI breakfast enhanced both response times and accuracy later in the morning when compared to a high GI breakfast and breakfast omission, particularly on the more cognitively demanding levels of the cognitive function tests. Furthermore, the low GI breakfast produced a smaller overall glycaemic response when compared to the high GI breakfast.

Overall, the findings indicate that a low GI breakfast is more beneficial, than both a high GI breakfast and breakfast omission, for cognitive function in adolescent schoolchildren across the school morning. However, further work is required to examine the optimal timing of breakfast and the effects of different macronutrients on cognitive function during the school morning. Furthermore, where possible given the ethical constraints of working with young people, more detailed mechanistic work should be undertaken to suggest potential mechanisms for nutritional effects on cognitive function.
Chapter VI

Exercise and Cognitive Function in Adolescent School Children

6.1: Introduction

There is increasing evidence that an acute bout of exercise enhances cognitive function in adult populations (Etnier et al., 1997; Lambourne & Tomporowski, 2010), but there are fewer studies examining the effects of exercise on cognitive function in young people. There is some evidence to suggest that exercise is also beneficial for cognitive function in young people, as evidenced by an overall effect size (ES) of 0.32 in the meta-analysis of Sibley & Etnier (2003). However, a number of moderator variables influenced the effect size, including the age of the participants. Specifically, whilst the largest effect size was seen for ‘middle school’ students (aged 8-11) (ES = 0.48), ‘high school’ students (aged 12-16) showed a smaller effect size (ES = 0.24) (Sibley & Etnier, 2003). The ‘high school’ age range (which corresponds to adolescence (Bogin, 1999)), also had fewer studies from which to calculate an effect size (k = 14), many of which were unpublished, thus making specific comparison between studies difficult.

It is suggested that cognitive function is of primary importance during adolescence due to the greater complexity of the academic work completed and the role of cognitive function in determining academic achievement (Cromer et al., 1990). The effects of exercise on cognitive function in adolescents may also be different to the more frequently reported effects in adults and younger children because adolescents are undergoing rapid growth and
changes in metabolism; thus their responses to exercise, and the subsequent effects on
cognitive function, may be different (Cromer et al, 1990; Kanarek, 1997). Specifically, the
findings in younger children (aged 3-11) cannot be generalised to adolescents, given that
younger children have a larger brain weight relative to their body weight and a 50% greater
metabolic rate per unit of brain weight (Hoyland et al, 2009), thus the effects of exercise on
cognitive function is likely to be different between these populations.

Relatively few studies have been published examining the acute effects of exercise on
cognitive function in adolescents. From the published studies, there is a general trend towards
exercise having a beneficial effect on adolescents’ cognitive function (e.g. Zervas et al, 1991;
assessed cognitive function following Physical Education lessons and, for example, the
findings indicated a greater accuracy of attention following a PE lesson, compared to resting
during a normal science lesson (Zervas et al, 1991). More recently, it has also been suggested
that both the type of exercise and the time of day may influence the effects of exercise on
cognitive function in adolescents.

Specifically, bilateral coordinative exercise (which increased activation in the frontal
lobe and cerebellum) was shown to be more beneficial for both the speed and accuracy of
attention than a normal sports lesson (Budde et al, 2008). However, the everyday
applicability of the exercise must be considered, and as the bilateral coordinative exercise
requires equipment and supervision, it is not practical in everyday school settings.
Furthermore, the time of day is also believed to play a role, with findings indicating that
exercise completed earlier in the day is beneficial, whereas exercise later in the school day
was detrimental, for mathematical computation among adolescents (Travlos, 2010).
Where positive effects on cognitive function have been seen following exercise, several mechanisms have been postulated to mediate such effects, including increased cerebral blood flow (Querido & Sheel, 2007) which enhances the delivery of glucose and oxygen to neural tissues and the clearance of carbon dioxide (Jorgensen et al, 2000). Although a topic of much debate, it has also been suggested that lactate may be oxidised by the brain (Schurr, 2006). Other authors have suggested that more general arousal mechanisms may be at work, whereby exercise increases physiological and/or cognitive arousal, thus enhancing cognitive function (Brisswalter et al, 2002). It is clear that more detailed mechanistic work needs to be undertaken, including in adolescent populations, to explain any exercise induced effects on cognitive function. Therefore, the present study will measure blood glucose, plasma insulin and blood lactate concentrations following exercise, as well as assessing mood in an adolescent population.

A limitation of the studies conducted in adolescents to date is that cognitive function has been measured immediately (or very soon, i.e. < 10 min) following exercise. However, in everyday school settings, it may be up to one hour between exercise (at break time or during a PE lesson) and the next academic lesson, where cognitive function is of interest for learning. Indeed, in adults, whilst it was hypothesised that the effects of exercise may decline with a greater time period before cognitive testing, the effect sizes were similar across different lengths of time between exercise and cognitive testing (Lambourne & Tomporowski, 2010). However, this has not been examined in adolescents.

Therefore, the aim of the present study was to address this void in the literature and examine the effects of exercise (which could easily be incorporated into the school morning, e.g. at break time) on subsequent cognitive function in adolescents. This study used a battery of cognitive function tests (visual search test, Stroop test and Sternberg paradigm), to assess
multiple components of cognitive function, extending previous work in the literature. Furthermore, mood and blood glucose, plasma insulin and blood lactate concentrations were assessed across the morning to allow a potential insight into the mechanisms for any effects of exercise on adolescents’ cognitive function.

6.2: Methodology

6.2.1: Participant Characteristics

Sixty schoolchildren aged 12 to 13 years were recruited to participate in the study. However, 15 participants failed to complete the study because they were either absent from school for one of the experimental trials (n = 11) or failed to comply with the dietary control conditions (n = 4). During familiarisation, simple measures of height, body mass and waist circumference were taken using the methods described in detail in section 3.3. For descriptive purposes, the anthropometric characteristics of the participants who completed the study (n = 45) are provided in table 6.1.

Table 6.1: Anthropometric characteristics of participants.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Age [yrs]</th>
<th>Height [cm]</th>
<th>Body Mass [kg]</th>
<th>BMI [kg.m⁻²]</th>
<th>Waist Circumference [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>15</td>
<td>13.2±0.2</td>
<td>159.2±7.3</td>
<td>45.4±7.0</td>
<td>17.8±2.0</td>
<td>65.0±4.3</td>
</tr>
<tr>
<td>Female</td>
<td>30</td>
<td>13.3±0.3</td>
<td>159.3±6.9</td>
<td>52.7±11.6</td>
<td>20.7±4.1</td>
<td>68.1±8.3</td>
</tr>
<tr>
<td>Overall</td>
<td>45</td>
<td>13.3±0.3</td>
<td>159.2±7.0</td>
<td>50.3±10.8</td>
<td>19.7±3.7</td>
<td>67.1±7.3</td>
</tr>
</tbody>
</table>

All values are mean ± standard deviation.
6.2.2: Study Design

The study was approved by Loughborough University Ethical Advisory Committee. Consent was gained from participants using the methods described in detail in section 3.2. In brief, a written parental informed consent form and health screen questionnaire was completed by participants’ parents or guardians prior to participation in the study.

Each participant undertook a familiarisation session, which preceded the first of two experimental trials by seven days. During familiarisation, the protocol of the study was explained and participants were provided with an opportunity to familiarise themselves with the methods involved, which included completing the battery of cognitive function tests and participants were provided with an opportunity to ask questions and clarify any part of the tests they did not fully understand.

The study employed a randomised crossover design, with participants blinded against trial condition until arrival at school on each day of testing. The experimental trials consisted of an exercise trial and a resting trial. Therefore, participants acted as their own controls. Trials were scheduled seven days apart and participants reported to school at the normal time. The experimental protocol is shown in figure 6.1.

Figure 6.1: Experimental protocol
Chapter VI: Exercise and Cognitive Function

Upon arrival at school participants rested for 10 min, then had a capillary blood sample taken and completed the mood questionnaire. The protocol commenced as participants began consuming their self-selected breakfast. Participants were given 15 min to consume breakfast. Capillary blood samples, the mood questionnaire and the cognitive function tests were completed during the 120 min monitoring period. On the exercise trial, participants completed 10 min of exercise 60 min into the monitoring period. On the resting trial, participants continued to rest during this time.

6.2.3: Dietary Control

Participants consumed a meal of their choice the evening before their first experimental trial and were asked to repeat this meal for their subsequent trial. Following this meal, participants were asked to observe an overnight fast from 10pm. In order to maintain euhydration, participants were allowed to drink water ad libitum during this time. In addition, participants were asked to avoid any unusually vigorous exercise for 24 hours prior to each experimental trial. Prior to each main trial a telephone call was made to participants to remind them of this information. On the day of each experimental trial, upon arrival at school participants were asked to indicate if they had followed the above requirements. Participants who had not followed these requirements were removed from the study (n = 4).

6.2.4: Capillary Blood Sampling

Capillary blood samples were taken at baseline and 30, 60 and 120 min after breakfast consumption on each trial using the methods described in section 3.6.2. The variables of
interest were blood glucose, plasma insulin and blood lactate concentrations, determined using the methods described in section 3.6.2.

6.2.5: Mood Questionnaire

The modified version of the ‘Activation-Deactivation Check List’ (ADACL), as described in section 3.5, was completed by participants at baseline and 30, 60 and 120 min following breakfast consumption. The ADACL provided a measure of participants’ self-report energy, tiredness, tension and calmness. In addition, three visual analogue (VAS) scales were used to provide a measure of participants’ hunger, fullness and concentration (see section 3.5). Both the ADACL and VAS scales allow comparisons between time points.

6.2.6: Cognitive Function Tests

The battery of cognitive function tests was administered via a laptop computer and was completed 30 min before and 45 min after the mid-morning bout of exercise (30 and 120 min following breakfast consumption). The battery of tests for this study consisted of the visual search test, the Stroop test and the Sternberg paradigm, which are described in detail in section 3.4.

6.2.7: Breakfast

In this study, participants were provided with a buffet and self-selected from these foods ad libitum, as described in section 3.7.1. On the first trial, the quantity of food taken by each participant was recorded and any leftovers weighed using a Salter 1029 WHDRT scale
(Salter, Hamburg, Germany) to allow determination of the breakfast consumed by each participant. On the subsequent trial, an identical breakfast was provided along with instructions that all the breakfast must be consumed within 15 min. All participants followed this instruction. The matched breakfast was used in the present study due to the well documented effects of breakfast consumption (chapter IV) and composition (chapter V) on cognitive function in adolescent populations. The breakfast consumed was analysed for energy content (kcal) and for the amount of carbohydrate (g), protein (g) and fat (g). The energy content and composition of the breakfast consumed is shown in table 6.2.

**Table 6.2: Breakfast consumed by participants**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [kcal]</td>
<td>397±172</td>
</tr>
<tr>
<td>Carbohydrate [g]</td>
<td>76.4±34.5</td>
</tr>
<tr>
<td>Protein [g]</td>
<td>8.1±3.8</td>
</tr>
<tr>
<td>Fat [g]</td>
<td>6.4±4.1</td>
</tr>
</tbody>
</table>

All values are mean ± standard deviation.

**6.2.8: Exercise Protocol**

On the exercise trial, 60 min following breakfast consumption, participants completed the mid-morning bout of exercise, as described in section 3.8. The duration of the exercise was chosen so it was sufficiently brief to fit into the school morning and reflected adolescents' usual physical activity patterns. Therefore, the exercise protocol has potential practical application to be incorporated into the school morning.
6.2.9: Statistical Analysis

The mood, blood glucose, plasma insulin and blood lactate data were analysed using PASW Statistics (Version 18, SPSS Inc., Chicago, Il, USA) via two-way Analysis of Variance (ANOVA) for repeated measures (trial by session time). Data are presented as mean ± S.E.M..

The cognitive function data were analysed using R (www.r-project.org, version 2.9.1). Linear mixed effects models were used to analyse the data, corrected for repeated measures with a random effect for each participant. Response time analyses were performed using the nlme package and accuracy analyses were performed with the lme4 package with a binomial outcome data distribution. Analyses were conducted using a three-way trial (exercise/resting) by session time (9.30am/11.00am) by test level (baseline/complex) interaction. Where the three-way interaction was not significant, a two-way trial by session time analysis was conducted. For all analyses, significance was set as p < 0.05.

6.3: Results

6.3.1: Trial order balance

To minimise the influence of possible learning effects on the results, trial order was counterbalanced across participants. However, with drop-outs (n = 11 due to absence from school and n = 4 due to failing to comply with the overnight fast) the final dataset included 20 participants that had completed the resting trial followed by the exercise trial, and 25 participants with the reverse trial order. Rather than removing valid data points to arrive at a fully counterbalanced set of trial orders, possible order effects were corrected for statistically
by including repeat test session number as a numerical co-variate, including linear and quadratic effects, where significant.

6.3.2: Exercise

Of the 45 adolescents who participated in the study, 23 (51.1%) completed all 10 repeats of level one of the MSFT without their heart rate reaching the threshold of 190 beats.min\(^{-1}\). Overall, participants ran for 7 ± 1 min (mean ± S.D.) and whilst running, the average heart rate was 178 ± 11 beats.min\(^{-1}\). The participants whose heart rate reached 190 beats.min\(^{-1}\) continued to walk for the remainder of the exercise, during which their heart rate was 151 ± 16 beats.min\(^{-1}\). However, the total exercise time (running and walking) for all participants was 10 min, with an overall average heart rate of 172 ± 17 beats.min\(^{-1}\).

6.3.3: Mood

Each dimension of mood assessed by the modified ADACL (energy, tiredness, tension and calmness) improved during the first 30 min of the trials (when breakfast was consumed), then remained similar until the end of the trials (main effects of time; energy: \(F_{(3,132)} = 16.4, p < 0.001\); tiredness: \(F_{(3,132)} = 19.1, p < 0.001\); tension: \(F_{(3,132)} = 5.2, p = 0.004\); calmness: \(F_{(3,132)} = 13.1, p < 0.001\)). However, the pattern of change in each dimension of mood was the same across the morning between the exercise and resting trials (trial by session time interactions, all \(p > 0.05\)).

As with the aforementioned dimensions of mood, there was a consistent effect of the time of morning on hunger, fullness and concentration, as assessed by the VAS scales. The
main changes coincided with the consumption of breakfast during the first 30 min of the trials, where hunger decreased, whilst fullness and concentration increased, before all 3 dimensions remained similar from 30 to 120 min during the rest of the trial (main effects of time; hunger: $F_{(3,114)} = 90.1$, $p < 0.001$; fullness: $F_{(3,114)} = 104.3$, $p < 0.001$; concentration: $F_{(3,114)} = 36.7$, $p < 0.001$). However, the pattern of change in hunger, fullness and concentration across the morning was not different between the exercise and resting trials (trial by session time interactions, all $p > 0.05$).

6.3.4: Cognitive Function Tests

For all cognitive tests the response times were first log transformed to normalise the distributions, which exhibited the right-hand skew typical of human response times. Minimum response cut-offs were then chosen based on what may reasonably be expected to be the fastest possible human response to the given stimuli (100 – 300 ms, depending on task complexity) to exclude unreasonably fast responses, which relate to response key presses before stimuli have been perceived. Maximum response time cut-offs were determined so as to remove unreasonably long right-hand tails for a normal distribution.

6.3.4.1: Visual Search Test

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, responses faster than 300 ms for both test levels and slower than 1500 ms for the baseline level and 10000 ms for the complex level were removed.
There was a significant three-way interaction for response times on the visual search test (trial by session time by test level interaction, $t_{(3,7301)} = 2.6$, $p = 0.009$, figure 6.2). Upon inspection of figure 6.2, response times increased by a similar magnitude across the morning on the exercise and resting trials on the baseline level (figure 6.2a). However, on the complex level, whilst response times were slower at 9.30 am on the exercise trial, response times improved by a greater amount across the morning on the exercise trial, when compared to the resting trial (figure 6.2b).

Accuracy: There was also a significant three-way interaction for accuracy on the visual search test (trial by session time by test level interaction, $z_{(3,7978)} = 2.0$, $p = 0.044$, figure 6.3). Upon inspection of figure 6.3, accuracy decreased by a similar amount across the morning on the exercise and resting trials on the baseline level (figure 6.3a). However, on the complex level, whilst accuracy was greatest at 9.30 am on the exercise trial, there was a greater decrease in accuracy across the morning on the exercise trial, when compared to the resting trial (figure 6.3b).
Figure 6.2a: Baseline level

Figure 6.2b: Complex level

Figure 6.2: Response times across the morning on the exercise and resting trials on the baseline (figure 6.2a) and complex (figure 6.2b) levels of the visual search test (trial by session time by test level interaction, p = 0.009)
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Figure 6.3a: Baseline level

Figure 6.3b: Complex level

Figure 6.3: Accuracy across the morning on the exercise and resting trials on the baseline (figure 6.3a) and complex (figure 6.3b) levels of the visual search test (trial by session time by test level interaction, p = 0.044)
6.3.4.2: Stroop Test

**Response Times:** Only the response times of correct responses were used for analysis. Using the methods previously described, responses quicker than 250 ms for both test levels and slower than 2500 ms for the baseline level and 4000 ms for the complex level were removed. There was no difference in the pattern of change in response times across the morning between the exercise and resting trials (trial by session time interaction, p = 0.109); nor was this effect different between the baseline and complex levels (trial by session time by test level interaction, p = 0.135).

**Accuracy:** There was no difference in accuracy across the morning between the exercise and resting trials (trial by session time interaction, p = 0.307); nor was this effect different between the different test levels (trial by session time by test level interaction, p = 0.440).

6.3.4.3: Sternberg Paradigm

**Response Times:** Only response times of correct responses were used for analysis. Using the methods previously described, responses faster than 200 ms and slower than 2000 ms for all memory loads were removed. The pattern of change in response times across the morning was not different on the exercise and resting trials between the different test levels (trial by session time by test level interaction, p = 0.838). However, across all test levels, whilst response times on the Sternberg paradigm improved across the morning on the exercise trial, they slowed across the morning on the resting trial (trial by session time interaction, t(3,12607) = 2.6, p = 0.010, figure 6.4).
Figure 6.4: Response times across the morning on the exercise and resting trials on the Sternberg paradigm (trial by session time interaction, p = 0.010)

Accuracy: There was no difference in accuracy across the morning between the exercise and resting trials (trial by session time interaction, p = 0.833), nor was this effect different between the different test levels (trial by session time by test level interaction, p = 0.199).

6.3.5: Capillary Blood Samples

6.3.5.1: Blood Glucose Concentration

Blood glucose concentrations were similar between the two trials at 0, 30 and 60 min (all p > 0.05), but were significantly higher at 120 min on the exercise trial compared to the resting trial (p < 0.001). This produced a significant trial by time interaction, where although the glycaemic responses were similar between trials from 0 to 60 min, blood glucose concentrations were better maintained at 120 min on the exercise trial, whereas they
continued to decrease on the resting trial (trial by session time interaction, $F_{(3,132)} = 8.4$, $p < 0.001$, figure 6.5).

**Figure 6.5:** Blood glucose concentrations across the morning on the exercise and resting trials. Data are mean ± S.E.M.

(trial by session time interaction, $p < 0.001$; * exercise > resting, $p < 0.001$)

### 6.3.5.2: Plasma Insulin Concentration

Plasma insulin concentrations were similar between the trials at 0, 30 and 60 min (all $p > 0.05$), but were significantly higher at 120 min on the exercise trial compared to the resting trial ($p = 0.024$). This produced a significant trial by time interaction, where although the insulinaemic responses were similar between trials from 0 to 60 min, plasma insulin concentrations were better maintained at 120 min on the exercise trial, whereas they continued to decrease on the resting trial (trial by session time interaction, $F_{(3,132)} = 3.7$, $p = 0.014$, figure 6.6).
6.3.5.3: Blood Lactate Concentration

Blood lactate concentrations were similar between the two trials at 0, 30 and 60 min (all p > 0.05), but were significantly higher at 120 min on the exercise trial compared to the resting trial (p = 0.005). This produced a significant trial by time interaction, where although the lactate response was similar between the trials form 0 to 60 min, blood lactate concentrations were better maintained at 120 min on the exercise trial, whereas they decreased at a greater rate on the resting trial (trial by session time interaction, \( F_{3,132} = 2.9, p = 0.038 \), figure 6.7).
6.4: Discussion

The main findings of the present study were that whilst a mid-morning bout of exercise was beneficial for some components of cognitive function (e.g. greater improvement in response times on the Sternberg paradigm), exercise did not affect (e.g. Stroop test performance) other components. The mid-morning bout of exercise also produced a speed-accuracy trade-off on the visual search test, whereby participants responded quicker following exercise, but as a result their responses also become less accurate. Finally, the mid-morning bout of exercise helped to maintain blood glucose and plasma insulin concentrations, whilst blood lactate concentrations were higher following exercise, when compared with continuing to rest.
6.4.1: Visual Search Test

Results from the present study suggest that at 9.30 am on the complex level of the visual search test, on the exercise trial (prior to the mid-morning bout of exercise), participants were slower and more accurate than at any other time point on either trial (figures 6.2 and 6.3), producing the significant three way interactions. The results suggest that following the exercise, later in the morning (at 11am), participants’ exhibit a speed-accuracy trade-off, whereby they respond quicker but also become less accurate.

The present study is the first to examine the effects of an exercise bout on adolescents’ performance of the visual search test. Interestingly, in the meta-analysis of Sibley and Etnier (2003), perceptual skills (which are assessed by the visual search test) showed the largest effect size (ES = 0.49) in studies examining physical activity and cognition in children. However, this ES is calculated from the findings of five unpublished studies; thus the findings should be interpreted cautiously.

One study to assess the effects of exercise on a perceptual task in an adult population recruited high level sport performers who had expertise in decision making sports, with results suggesting response times on the test of perception were quicker immediately following 20 min cycling at 50% maximum power (Davranche & Audiffren, 2004). The authors proposed that an underlying cause for these effects was an increase in arousal, which enhanced cognitive function (Davranche & Audiffren, 2004). Interestingly, should exercise also increase arousal in an adolescent population (and if this effect is still evident 45 min after exercise), the findings of the present study would suggest that such an increase in arousal produces a speed accuracy trade off, whereby adolescents respond quicker, but as a result they also become less accurate following exercise on the perceptually demanding complex level of the visual search test (when compared to pre-exercise levels).
6.4.2: Stroop Test

Results from the present study suggest that completing a mid-morning bout of exercise has no effect on adolescents’ response times or accuracy on the Stroop test. No studies to date have examined the acute effects of a bout of exercise on adolescents’ performance on the Stroop test, a classical measure of selective attention and the ability to suppress an automated response (MacLeod, 1991; van Zomeren & Brouwer, 1992). However, several studies have examined the effects of exercise on attention, albeit in different age groups and using different tests of attention.

One such study showed that 7 and 10 year old males who completed a 30 min bout of cycling (at a heart rate of approximately 130 beats.min\(^{-1}\)) showed an improvement in response times on a test of attention created in Matlab, compared to those who continued to rest (Ellemberg & St-Louis-Deschênes, 2010). Furthermore, as was the case in the present study, there was no effect on the accuracy of responses (Ellemberg & St-Louis-Deschênes, 2010). However, the study employed a cross-sectional design, used a different test of attention to the present study and used participants who were younger than in the present study. Thus, the present study advances knowledge in the area by employing a well known test of selective attention (Stroop test) and focusing on an adolescent population.

An earlier study, which included some results from adolescents in their pooled data also showed that attention was not affected by exercise (completing a physical education lesson), compared to resting during a science lesson (Raviv & Low, 1990), supporting the findings of the present study. Interestingly, another study to employ an adolescent population examined the longer term effects of a training programme on performance of an attention demanding test after a 20 min bout of treadmill running (Zervas et al, 1991). Whilst the authors did not observe an effect of the long-term training programme, they did note that.
immediately following the 20 min bout of exercise, there was an improvement in both the speed and accuracy of responses. However, these observations were made in comparison to a control group using a cross-over study design, thus a number of factors could confound study outcomes. Thus, the present study is the first to assess the effects of exercise on adolescents’ performance on the Stroop test, with results indicating that 45 min following the exercise, there is no effect on either response times or accuracy.

6.4.3: Sternberg Paradigm

The findings of the present study indicate that response times on the Sternberg paradigm were improved across the morning following exercise, compared to the resting trial where response times increased across the morning (figure 6.4). However, there was no effect of the exercise on the accuracy of responses on the Sternberg paradigm. Overall, as there was an improvement in response times which was combined with no change in accuracy, the findings of the present study suggest exercise was beneficial for the adolescents’ working memory.

No published studies have previously examined the acute effects of a bout of exercise on memory function in an adolescent population. However, in their meta-analysis, Sibley and Etnier (2003) included seven unpublished studies which examined the effects of exercise on memory function in young people (4 to 18 years old). Their findings indicated that memory was the only component of cognitive function not to be affected by exercise (ES = 0.03) (Sibley & Etnier, 2003). However, comparisons between the studies included in the earlier meta analysis and the present study must be made cautiously for a number of reasons, such as the present study employs only 12 and 13 year olds, whereas the meta analysis included 4 to
18 year olds, and limited details were provided on the studies included in the meta analysis, so the studies cannot be compared on the basis of age group, the exercise conducted (mode, duration, intensity), the component of memory assessed and the timing of the cognitive function tests. However, the findings of the present study do suggest that the speed of working memory is enhanced in adolescents following exercise, whilst the accuracy of working memory is unaffected.

6.4.4: Mechanisms

The mechanisms explaining the effects of exercise on cognitive function in an adolescent population were not directly investigated in the present study. However, blood glucose and plasma insulin concentrations were better maintained following the mid-morning bout of exercise, whereas they continued to decrease on the resting trial (figures 6.5 and 6.6). As glucose is the main fuel used by the brain, blood glucose concentrations (and plasma insulin concentrations due to the role of insulin in glucose uptake) are key when examining effects on cognitive function. In the present study, there was a general pattern for an improvement in response times following exercise, which could be explained by the higher blood glucose and plasma insulin concentrations following exercise.

However, blood glucose and plasma insulin concentrations are not the only potential mechanism to explain the effects of exercise on cognitive function. It has also been suggested that lactate may be oxidised by the brain (Schurr, 2006). However, this topic is poorly understood, with some evidence suggesting that lactate is only oxidised by the brain during hypoglycaemia (Maran et al, 1994). Should lactate only be oxidised by the brain under hypoglycaemic conditions, it is not likely to have affected cognitive function in the present
study, because the participants were euglycaemic during the postprandial period. However, whilst it is not possible to suggest exact mechanistic pathways from the present study, lactate concentrations were higher following the mid-morning bout of exercise (figure 6.7) and the role of lactate is, at the very least, interesting and warrants further investigation.

Several other mechanisms have been suggested to mediate the effects of exercise on cognitive function, including increased cerebral blood flow, which in combination with higher glucose and insulin concentrations, enhances the delivery of glucose and oxygen to neural tissues and also enhances the clearance of waste products such as carbon dioxide (Jorgensen et al, 2000). Furthermore, other psychological mechanisms have been postulated, such as increases in arousal (Brisswalter et al, 2002) and improvements in mood (shown in the present study by lower self-report tiredness on the exercise trial), which could enhance cognitive function. Another potential mechanism is changes in signalling within the brain, with future research needed to extend the work that has been done looking at event related potentials (Hillman et al, 2009; Stroth et al, 2009). However, from the findings of the present study it is only possible to speculate on such mechanisms, but blood glucose, plasma insulin, blood lactate and mood data are available, an advance on previous studies in the area.

**6.4.5: Summary and Future Research Directions**

In summary, the findings of the present study suggest that whilst moderate intensity exercise 45 min before computer based tests enhances some components of cognitive function, exercise did not affect other components of cognitive function in an adolescent population. However, it is clear that more work is required in this area, including studies examining the effects of the intensity, duration and mode of exercise on cognitive function in
adolescents, the time for which the beneficial effects of exercise exist, as well as more
detailed mechanistic work examining the causes of any exercise induced changes in cognitive
function.
Chapter VII

Breakfast Glycaemic Index and Exercise: The Combined Effects on Adolescents’ Cognitive Function

7.1: Introduction

Whilst the individual effects of breakfast consumption (chapter IV), breakfast glycaemic index (GI) (chapter V) and a mid-morning bout of exercise (chapter VI) on adolescents’ cognitive function have been considered in this thesis and to a limited extent in earlier studies, the combined effects of breakfast and exercise have not been previously examined. However, in reality, breakfast and exercise do not exist as separate entities and in everyday situations, it is likely that a young person will consume breakfast, and then exercise either before school, at morning break or during a physical education class.

The findings presented in chapter V suggested that, across the tests employed, the low GI breakfast was the most beneficial for adolescents’ cognitive function. There is also evidence from the literature which suggests that a low GI breakfast is the most beneficial for adolescents’ cognitive function, especially later in the morning (i.e. 120-180 min following breakfast consumption) (Wesnes et al, 2003; Micha et al, 2010). However, it must be acknowledged that other findings have indicated that a high GI breakfast is most beneficial for cognitive function (Micha et al, 2008; Smith & Foster, 2008). However, such studies have often used high and low GI breakfasts which are not matched on key variables such as energy and carbohydrate content, and have measured only limited components of cognitive function. A recent review (Hoyland et al, 2009) concluded that a low GI breakfast appears to be the
most beneficial for cognitive function in young people, with the results presented in chapter V of this thesis confirming these findings and extending them to an adolescent population.

In addition, the findings presented in chapter VI suggest that a mid-morning bout of exercise may also be beneficial for some components of adolescents’ cognitive function, whereas it does not affect other components. The evidence in the literature is also mixed, with some studies showing a beneficial effect of exercise (e.g. Zervas et al, 1991; McNaughten & Gabbard, 1993; Budde et al, 2011), whereas others show no effect of exercise (e.g. Raviv & Low, 1990; Stroth et al, 2009). Furthermore, few studies have examined the effects of exercise on subsequent cognitive function later in the morning (as addressed in chapter VI), with most measures of cognitive function being made either during, or immediately post-exercise.

As detailed in the previous experimental chapters, the mechanisms mediating the effects of breakfast consumption, breakfast GI and a mid-morning bout of exercise on cognitive function are poorly understood. Given that some believe glucose is the only fuel that can be used in the central nervous system, it is thought that glucose availability may play a key role (as addressed in previous chapters) (Dye et al, 2000). Furthermore, insulin concentrations (given the key role of insulin in determining glucose uptake by tissues) have also been suggested as a potential mediating factor. However, as outlined in chapter V, glucose concentrations cannot be the only mediator, given that a high GI breakfast produced higher blood glucose concentrations, whereas a low GI breakfast produced enhanced cognitive performance. Moreover, some authors have suggested that lactate may be oxidised by the brain (Schurr, 2006), thus blood lactate concentrations will also be measured in the present study. Throughout this thesis though, the primary purpose has not been to propose detailed mechanisms. However, by continuing to measure blood glucose, plasma insulin and
blood lactate concentrations, the mechanisms mediating the combined effects of breakfast GI and exercise on adolescents’ cognitive function can be speculated upon further.

Therefore, the aim of the present study is to examine the combined effects of a high and low GI breakfast and 10 min of mid-morning exercise on cognitive function in adolescent school children. The study allocated participants to matched high and low GI breakfast groups, within which participants completed both an exercise and resting trial. The exercise used is the same as used in chapter VI, thus the exercise is sufficiently brief to be able to fit into the school morning and has potential practical applications to be incorporated in everyday settings.

7.2: Methodology

7.2.1: Participant Characteristics

Forty-two adolescents aged 11 to 13 years old were recruited to participate in the study. During familiarisation, simple measures of height, body mass and waist circumference were taken using the methods described in detail in section 3.3. Table 7.1 provides the anthropometric characteristics of the participants and a comparison between the high and low GI breakfast groups.
## Table 7.1: Anthropometric characteristics of participants

<table>
<thead>
<tr>
<th></th>
<th>Age [yrs]</th>
<th>Height [cm]</th>
<th>Sitting Height [cm]</th>
<th>Body Mass [kg]</th>
<th>BMI [kg.m(^{-2})]</th>
<th>Waist Circumference [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High GI Group</td>
<td>12.5±0.5</td>
<td>154.1±7.5</td>
<td>80.3±5.3</td>
<td>45.8±9.9</td>
<td>19.1±3.0</td>
<td>64.7±6.4</td>
</tr>
<tr>
<td>Low GI Group</td>
<td>12.4±0.4</td>
<td>154.4±8.0</td>
<td>80.2±4.2</td>
<td>43.6±7.5</td>
<td>18.2±2.2</td>
<td>65.4±6.0</td>
</tr>
<tr>
<td>Comparison (p value)(^a)</td>
<td>0.625</td>
<td>0.903</td>
<td>0.957</td>
<td>0.434</td>
<td>0.274</td>
<td>0.718</td>
</tr>
</tbody>
</table>

Data are mean ± standard deviation.
\(^a\) comparison performed using one way analysis of variance

### 7.2.2: Study Design

The study was approved by Loughborough University Ethical Advisory Committee. Consent was gained from participants using the methods described in detail in section 3.2. In brief, participants were recruited from a local school and in accordance with the ethical guidelines of the British Education Research Authority, school level consent was obtained from head teachers. In addition, written parental informed consent was obtained and a health screen questionnaire completed to ensure all participants were in good health.

Each participant undertook a familiarisation session followed by two experimental trials. During familiarisation, which preceded the first experimental trial by 7 days, the protocol of the study was explained to participants and they were provided with an opportunity to familiarise themselves with the methods involved. Participants were allowed to repeat the cognitive function tests until they felt comfortable with them, to negate any potential learning effects.

The study employed a mixed research design, with participants randomly allocated to a high or low glycaemic index (GI) breakfast group. Within each group, participants...
completed an exercise and resting trial, in a randomised, order balanced crossover design. The experimental (exercise and resting) trials were scheduled 7 days apart and participants reported to school at the usual time. Figure 7.1 shows the experimental protocol.

Upon arrival at school, participants rested for 10 min in a seated position, then a capillary blood sample was taken and the mood questionnaire completed. The protocol commenced as participants started breakfast, which they were given 15 minutes to consume. Capillary blood samples, the mood questionnaire and the cognitive function tests were completed during the subsequent monitoring period. The monitoring period was selected based upon recommendations which suggest that 120 min is a sufficient period of time to elicit the different glycaemic responses between the high and low GI breakfasts (Brouns et al, 2005). This is also the period of time after which it is suggested the effects of; breakfast consumption (chapter IV), breakfast GI (chapter V) and a mid-morning bout of exercise (chapter VI), will become apparent in young people (Wesnes et al, 2003; Benton et al, 2007; Micha et al, 2008).
7.2.3: Dietary Control

Participants were asked to consume a meal of their choice the evening before their first experimental trial and repeated this meal for the subsequent trial. Following this meal, participants fasted from 10pm. In order to maintain euhydration, participants were allowed to drink water ad libitum during this time. In addition, participants avoided any unusually vigorous exercise for 24 h prior to each experimental trial. Prior to each experimental trial a telephone call was made to participants to remind them of this information. Upon arrival at school, participants were asked to indicate if they had followed the above requirements. Participants who had not followed these requirements were removed from the study.

7.2.4: Mood Questionnaire

The modified version of the ‘Activation-Deactivation Check List’ (ADACL) as described in detail in section 3.5, was completed by participants at baseline and 30, 60 and 120 min following breakfast consumption. The mood questionnaire provided a measure of participants’ self-report energy, tiredness, tension and calmness. In addition, three visual analogue (VAS) scales were used to provide a measure of participants’ hunger, fullness and concentration. Both the ADACL and VAS scales allow comparison between time points.

7.2.5: Capillary Blood Sampling

Capillary blood samples were taken at baseline and 30, 60 and 120 min after breakfast consumption on each trial, using the methods described in detail in section 3.6.1.
Subsequently, blood glucose, plasma insulin and blood lactate concentrations were determined using the methods described in section 3.6.2.

7.2.6: Cognitive Function Tests

The battery of cognitive function tests was administered via a laptop computer, 30 and 120 min following breakfast consumption. The battery of tests for this study consisted of the visual search test, the Stroop test and the Sternberg paradigm, which are described in detail in section 3.4.

7.2.7: Breakfast

The high and low GI breakfasts provided in the present study are described in detail in section 3.7.2. Breakfast was provided after the resting measures had been taken and participants were given 15 min to consume breakfast.

7.2.8: Exercise Protocol

On the exercise trial, 60 min following breakfast consumption, participants completed the mid-morning bout of exercise, as described in section 3.8. The duration of the exercise was chosen so it was sufficiently brief to fit into a normal school morning and reflected adolescents’ usual physical activity patterns. Therefore, the exercise protocol has potential practical application to be incorporated into the school morning.
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7.2.9: Statistical Analysis

The mood, blood glucose, plasma insulin and blood lactate data were analysed using PASW Statistics (Version 18, SPSS Inc., Chicago, IL, USA) via three-way Analysis of Variance (ANOVA) (breakfast by exercise by time) with repeated measures on two factors (exercise and session time). Data are presented as mean ± S.E.M..

The cognitive function data were analysed using R (www.r-project.org, version 2.9.1). All analyses were conducted using a four-way ANOVA (breakfast by exercise by session time by test level), with repeated measures on three factors (exercise, session time and test level). For all analysis, significance was set as p < 0.05.

7.3: Results

7.3.1: Exercise

Of the 42 adolescents who completed the study, 29 (69.0%) completed all 10 repeats of level one of the MSFT without their heart rate reaching the threshold of 190 beats.min⁻¹. Overall, participants ran for 9 ± 2 min (mean ± S.D.) and whilst running the average heart rate was 173 ± 13 beats.min⁻¹. Participants whose heart rate reached 190 beats.min⁻¹ continued to walk for the remainder of the exercise, during which their heart rate was 149 ± 19 beats.min⁻¹. However, total exercise time (walking and running) for all participants was 10 min, during which the overall average heart rate was 170 ± 15 beats.min⁻¹. In addition, there were no differences in the total running time, walking time, running heart rate, walking heart rate or overall heart rate between the high and low GI breakfast groups (all p > 0.05).
7.3.2: Mood

For each dimension of mood assessed by the modified ADACL, there was no difference in the pattern of change across the morning on the exercise and resting trials, between the high and low GI breakfast groups (3-way breakfast by exercise by time interactions, all p > 0.05). Furthermore, when considering the high and low GI breakfast groups separately, there was no effect of exercise on any components of mood (2-way exercise by time interactions, all p > 0.05). However, there was a significant effect of the time of morning on each component of mood, with energy increasing following breakfast consumption (from 0-30 min), whereas tiredness, tension and calmness all decreased during this time, before all components of mood stabilised during the 30-120 min monitoring period (main effects of time; energy: F\textsubscript{(3,41)} = 17.4, p < 0.001; tiredness: F\textsubscript{(3,41)} = 22.8, p < 0.001; tension: F\textsubscript{(3,41)} = 7.4, p = 0.001; calmness: F\textsubscript{(3,41)} = 14.9, p < 0.001).

Similar to mood, there was no difference in the pattern of change across the morning on the exercise and resting trials, between the high and low GI breakfast groups for hunger, fullness and concentration, as assessed by the VAS scales (3-way breakfast by exercise by time interactions, all p > 0.05). Also, when considering the high and low GI breakfast groups separately, there was no effect of exercise on hunger, fullness or concentration in either the high or low GI breakfast groups (2-way exercise by time interactions, all p > 0.05). However, there was a main effect of the time of morning on each dimension of the VAS scales, with hunger decreasing following breakfast consumption (from 0 to 30 min), whereas fullness and concentration increased during this time (main effects of time; hunger: F\textsubscript{(3,41)} = 17.4, p < 0.001; fullness: F\textsubscript{(3,41)} = 83.7, p < 0.001; concentration: F\textsubscript{(3,41)} = 30.0, p < 0.001).
7.3.3: Cognitive Function Tests

For all timed cognitive tests, the response times were first log-transformed to normalise the distributions, which exhibited the right-hand skew typical of human response times. Minimum response time cut-offs were chosen based on what may reasonably be expected to be the fastest possible human response to the given stimuli (100-300 ms depending to task complexity) to exclude unreasonably fast responses, which relate to key presses before stimuli have even been perceived. Maximum response time cut-offs were determined so as to remove unreasonably long right-hand tails for a normal distribution.

7.3.3.1: Visual Search Test

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, a minimum response time cut-off of 300 ms for both test levels and a maximum response time cut-off of 1500 ms for the baseline level and 10000 ms for the complex level was set. The effect of the mid-morning bout of exercise on response times was not different between the high and low GI breakfast groups or between the baseline and complex levels of the visual search test (4-way breakfast by exercise by session time by test level interaction, \( p = 0.999 \)). However, when analysing the data from the baseline level separately, there was a significant three-way interaction, in that response times slowed across the morning on all trials with the exception of the resting trial following the high GI breakfast (3-way breakfast by exercise by session time interaction, \( F_{(1,3411)} = 5.0, p = 0.026 \), figure 7.2). When analysing data from the complex level separately, the three-way interaction was not significant (\( p = 0.229 \)), suggesting that breakfast GI and a mid-morning bout of exercise did not combine to affect response times on complex level of the visual search test.
Figure 7.2a: High GI breakfast

Figure 7.2b: Low GI breakfast

Figure 7.2: Response times across the morning following the high GI (figure 7.2a) and low GI (figure 7.2b) breakfasts, on the exercise and resting trials, on the baseline level of the visual search test

(3-way breakfast by exercise by session time interaction, p = 0.026)
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Accuracy: The effect of the mid-morning bout of exercise on accuracy was not different between the high and low GI breakfast groups or between the baseline and complex levels of the visual search test (4-way breakfast by exercise by session time by test level interaction, $p = 0.806$). Similarly, when analysing the baseline and complex level data separately, there was no difference in accuracy across the morning between the high and low GI breakfast groups on the exercise and resting trials (3-way breakfast by exercise by session time interactions, baseline level: $p = 0.828$; complex level: $p = 0.760$). Therefore, overall breakfast GI and a mid-morning bout of exercise did not affect accuracy on the visual search test.

7.3.3.2: Stroop Test

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, a minimum response time cut-off of 250 ms for both test levels and a maximum response time cut-off of 2500 ms for the baseline level and 4000 ms for the complex level was set. The effect of the mid-morning bout of exercise on response times was not different between the high and low GI breakfast groups or between the baseline and complex levels of the Stroop test (4-way breakfast by exercise by session time by test level interaction, $p = 0.054$). However, this interaction did approach significance.

Upon further analysis of the baseline level, the pattern of change in response times across the morning was the same between the high and low GI breakfast groups and between the exercise and resting trials (3-way breakfast by exercise by session time interaction, $p = 0.698$). However, on the complex level, there was a significant three-way interaction (breakfast by exercise by session time interaction, $F_{(1,5890)} = 6.4$, $p = 0.012$, figure 7.3), in that the greatest improvement in response times was seen on the exercise trial following a
low GI breakfast, followed by similar improvements across the morning on the resting trials, whereas response times were unchanged across the morning on the exercise trial following the high GI breakfast. Therefore, overall a low GI breakfast followed by a mid-morning bout of exercise was the most beneficial for response times on the Stroop test.

Accuracy: The effect of the mid-morning bout of exercise on accuracy was not different between the high and low GI breakfast groups or between the baseline and complex levels of the Stroop test (4-way breakfast by exercise by session time by test level interaction, \( p = 0.689 \)). Similarly, when analysing the baseline and complex level data separately, there was no difference in accuracy across the morning between the high and low GI breakfast groups on the exercise and resting trials on either test level (3-way breakfast by exercise by session time interactions, baseline level: \( p = 0.907 \); complex level: \( p = 0.433 \)). Therefore, overall breakfast GI and a mid-morning bout of exercise did not affect accuracy on the Stroop test.

7.3.3.3: Sternberg Paradigm

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, a minimum response time cut-off of 200 ms and a maximum response time cut-off of 2000 ms was set for all test levels. The effect of the mid-morning bout of exercise on response times was not different between the high and low GI breakfast groups or between the different test levels of the Sternberg paradigm (4-way breakfast by exercise by session time by test level interaction, \( p = 0.128 \)).

When analysing the test levels individually, on both the one- and three-item levels, the pattern of change in response times across the morning following the high and low GI
Figure 7.3a: High GI breakfast

Figure 7.3b: Low GI breakfast

**Figure 7.3:** Response times across the morning following the high GI (figure 7.3a) and low GI (figure 7.3b) breakfasts, on the exercise and resting trials, on the complex level of the Stroop test (3-way breakfast by exercise by session time interaction, p = 0.012)
breakfasts was similar between the exercise and resting trials (3-way breakfast by exercise by session time interactions: one-item level p = 0.928, three-item level p = 0.189). However, on the five-item level, there was a significant three-way interaction (breakfast by exercise by session time interaction, F_{(1,4321)} = 5.5, p = 0.019, figure 7.4), in that following the low GI breakfast response times improved by a similar magnitude across the morning on both the exercise and resting trials, whereas following the high GI breakfast response times improved across the morning on the exercise trial, but remained unchanged across the morning on the resting trial. Therefore, overall whilst response times improved across the morning following a low GI breakfast regardless of exercise, following a high GI breakfast response times only improved across the morning on the exercise trial.

*Accuracy:* The effect of the mid-morning bout of exercise on accuracy was not different between the high and low GI breakfast groups or between the different levels of the Sternberg paradigm (4-way breakfast by exercise by session time by test level interaction, p = 0.211). Similarly, when analysing each test level separately, there was no difference in accuracy across the morning between the high and low GI breakfast groups on the exercise and resting trials on any test level (3-way breakfast by exercise by session time interactions, one-item level: p = 0.052; three-item level: p = 0.114; five-item level: p = 0.730). Therefore, overall breakfast GI and a mid-morning bout of exercise did not affect accuracy on the Sternberg paradigm.
Figure 7.4a: High GI breakfast

Figure 7.4b: Low GI breakfast

Figure 7.4: Response times across the morning following the high GI (figure 7.4a) and low GI (figure 7.4b) breakfasts, on the exercise and resting trials, on the five-letter level of the Sternberg paradigm

(3-way breakfast by exercise by session time interaction, p = 0.019)
7.3.4: Capillary Blood Samples

7.3.4.1: Blood Glucose Concentration

There was no difference in the pattern of change in blood glucose concentrations across the morning between the exercise and resting trials, between the high and low GI breakfast groups (3-way breakfast by exercise by time interaction, $F_{(3,120)} = 2.6$, $p = 0.053$, figure 7.5). However, there was a tendency for this interaction to be significant, which upon inspection of figure 7.5 would appear to be due to an elevation of blood glucose concentration following the exercise (at 120 min), but this only occurs following the high GI breakfast. Indeed, following the high GI breakfast, whilst blood glucose concentrations were similar at 0, 30 and 60 min (all $p > 0.05$), blood glucose concentrations were significantly higher following the exercise (at 120 min), when compared to the resting trial ($p < 0.001$). However, following the low GI breakfast, there was no difference in blood glucose concentrations between the exercise and resting trials at any time point (all $p > 0.05$).

7.3.4.2: Plasma Insulin Concentration

Analysis revealed a significant three-way (breakfast by exercise by time) interaction for plasma insulin concentrations ($F_{(3,120)} = 4.2$, $p = 0.007$, figure 7.6). Upon inspection of figure 7.6, it appears that this is due to an elevation of plasma insulin concentration following the exercise (at 120 min), but only following the high GI breakfast. Indeed, following the high GI breakfast, whilst plasma insulin concentrations were similar at 0, 30 and 60 min (all $p > 0.05$), they were significantly higher following the exercise (at 120 min), when compared to the resting trial ($p = 0.003$). However, following the low GI breakfast, there was no difference in plasma insulin concentrations between the trials at any time point (all $p > 0.05$).
**Figure 7.5a:** High GI breakfast

(* exercise > resting, p < 0.001)

**Figure 7.5b:** Low GI breakfast

**Figure 7.5:** Blood glucose concentrations across the morning following the high GI (figure 7.5a) and low GI (figure 7.5b) breakfasts, on the exercise and resting trials. Data are mean ± S.E.M..

(3-way breakfast by exercise by time interaction, p = 0.053)
**Figure 7.6a:** High GI breakfast

(* exercise > resting, p = 0.003)

**Figure 7.6b:** Low GI breakfast

*Figure 7.6:* Plasma insulin concentrations across the morning following the high GI (figure 7.6a) and low GI (figure 7.6b) breakfasts, on the exercise and resting trials. Data are mean ± S.E.M..

(3-way breakfast by exercise by time interaction, p = 0.007)
7.3.4.3: Blood Lactate Concentration

There was no difference in the pattern of change in blood lactate concentrations across the morning between the exercise and resting trials, between the high and low GI breakfast groups (3-way breakfast by exercise by time interaction, $p = 0.161$). However, upon inspection of figure 7.7, it can be seen that following the low GI breakfast, whilst blood lactate concentrations were similar at 0, 30 and 60 min (all $p > 0.05$), blood lactate concentrations were higher at 120 min on the exercise trial, when compared to the resting trial ($p = 0.001$). Similarly, following the high GI breakfast, blood lactate concentrations were similar at 0, 30 and 60 min (all $p > 0.05$), though they tended to be higher at 120 min on the exercise trial, when compared to the resting trial ($p = 0.06$), though this did not reach statistical significance.
Figure 7.7a: High GI Breakfast

Figure 7.7b: Low GI Breakfast

(* exercise > resting, p = 0.001)

Figure 7.7: Blood lactate concentrations across the morning following the high GI (figure 7.7a) and low GI (figure 7.7b) breakfasts, on the exercise and resting trials. Data are mean ± S.E.M.

(3-way breakfast by exercise by time interaction, p = 0.161)
7.4. Discussion

The main findings of the present study were that following a low GI breakfast response times improved across the morning on the Stroop test and Sternberg paradigm on both the exercise and resting trials. Furthermore, the mid-morning bout of exercise conferred an additional benefit for response times on the Stroop test, following the low GI breakfast. However, there was no effect of breakfast GI or a mid-morning bout of exercise on accuracy across the cognitive function tests, nor did breakfast GI and exercise exert a combined effect on accuracy. Furthermore, breakfast GI and a mid-morning bout of exercise did not affect mood in the adolescents tested. However, following the mid-morning bout of exercise in those who had consumed a high GI breakfast, blood glucose and plasma insulin concentrations were higher than in the resting trial, whilst blood lactate concentrations were higher following the mid-morning bout of exercise (compared to resting) following the low GI breakfast.

7.4.1: Visual Search Test

The findings of the present study indicate that performance on the complex level of the visual search test was not different across the morning on the exercise and resting trials following the high and low GI breakfasts. However, on the baseline level, response times slowed across the morning on all trials, except the resting trial following a high GI breakfast (figure 7.2). However, given that these findings are only evident on the baseline (easy) level of the visual search test, and the lack of significant results on the complex level and the non-significant 4-way interaction on the visual search test, these results do not suggest that breakfast GI and a mid-morning bout of exercise combine to affect visual perception (as
assessed by the visual search test). Rather, these results suggest that consuming a high GI breakfast followed by resting may be beneficial for simple response times (requiring little complex cognitive functions and executive control). These findings are similar to those of Micha et al (2008) who found that a high GI breakfast was more beneficial for the speed of information processing, when compared with a low GI breakfast, though the earlier study did not examine the combined effects of breakfast GI and exercise, as in the present study. However, given that the beneficial effect of the high GI breakfast followed by resting is not repeated across the baseline levels of the other cognitive function tests, there is only very limited support for this suggestion in the present study.

The findings presented in chapter V suggested that a low GI breakfast was the most beneficial for performance on the visual search test, especially in comparison with following a high GI breakfast, though the findings of the present study suggest no difference between the high and low GI breakfasts. However, in the present study breakfast GI was a between subject factor, thus comparisons between the high and low GI breakfast groups are limited, despite the fact that there were no significant differences between the groups (table 7.1).

Overall, the findings of the present study suggest that neither breakfast GI nor a mid-morning bout of exercise influence adolescents’ performance on the visual search test. In addition, the study builds on other studies in the literature and in this thesis, by showing that there are no combined effects of breakfast GI and a mid-morning bout of exercise on visual perception in adolescents, as assessed by the visual search test.
7.4.2: Stroop Test

The findings of the present study suggest that response times on the complex level of the Stroop test are enhanced across the morning following a low GI breakfast (on both the exercise and resting trials), which is in line with the findings presented in chapter V. However, it has previously been suggested that a high GI breakfast is beneficial for performance on the Stroop test, but only when the breakfast also had a high glycaemic load (GL) (Micha et al, 2008), whereas other studies have reported no effects of breakfast GI or GL on adolescents' performance on the Stroop test (Micha et al, 2010). However, these earlier studies have suffered from a number of methodological weaknesses, including: providing meals of differing GI/GL which are not matched on other key variables (such as energy and carbohydrate content) (Micha et al, 2008; Micha et al, 2010), and not reporting whether performance on the Stroop test was assessed via response times and/or accuracy.

In chapter VI, the findings indicated that exercise did not affect response times on the Stroop test. However, the findings of the present study suggest that the effects of exercise on response times on the Stroop test depended upon the GI of the breakfast. That is, following a low GI breakfast exercise was beneficial for response times on the Stroop test, whereas following the high GI breakfast response times were unchanged across the morning on the exercise trial. Whilst the studies presented here are the first to assess the effects of exercise on adolescents’ performance on the Stroop test, other studies have used other tests of attention, with conflicting findings. For example, response times on a test of attention created in Matlab were improved following 30 min cycling (at a heart rate of approximately 130 beats.min$^{-1}$) in 7 and 10 year olds (Ellemberg & St-Louis-Deschênes, 2010), and response times (and accuracy) were also enhanced immediately following 20 min treadmill running in adolescents, albeit compared to a control group using a crossover study design (Zervas et al,
1991). In contrast to these findings, it has also been reported that attention was not affected following a physical education lesson, when compared to following a science lesson (Raviv & Low, 1990).

Therefore, the evidence is mixed regarding the effects of exercise on adolescents’ attention, with factors such as; the age of the participants, the mode of exercise completed, the timing of the cognitive assessment relative to the exercise and the breakfast GI all influencing the effects on subsequent attention. However, the present study advances knowledge in the area by using a well known test of selective attention (Stroop test) and shows that whilst response times on the Stroop test are improved across the morning following a low GI breakfast regardless of exercise (though the improvement was greatest on the exercise trial), following a high GI breakfast response times remained unchanged across the morning on the exercise trial, though they improved across the morning on the resting trial.

7.4.3: Sternberg Paradigm

In the present study, the findings indicate that performance on the one- and three-letter levels of the Sternberg paradigm was similar across the morning on the exercise and resting trials following both the high and low GI breakfasts. However, on the five-letter level, performance improved across the morning following the low GI breakfast, regardless of whether exercise had been performed (figure 7.4b). However, following the high GI breakfast, whilst response times improved across the morning following the mid-morning bout of exercise, they remained similar across the morning on the resting trial (figure 7.4a). Completing the mid-morning bout of exercise also led to enhanced accuracy across the
morning following the high GI breakfast (figure 7.5), but this effect was only evident on the one-letter level.

The findings of chapter V also indicate that a low GI breakfast was beneficial for adolescents’ response times on the Sternberg paradigm, in accordance with the improvement in response times seen across the morning in the present study following the low GI breakfast, regardless of whether exercise had been performed (figure 7.4b). These findings are also consistent with previous findings in the literature, which show that the response times on a test of working memory were enhanced following a low GI breakfast, when compared to both a high GI breakfast and breakfast omission, in 9 to 16 year olds (Wesnes et al, 2003). Therefore, the findings of the present study add weight to the available evidence suggesting that a low GI breakfast is beneficial for the speed of adolescents’ working memory, whilst also demonstrating that this effect is evident regardless of a mid-morning bout of exercise.

However, the mid-morning bout of exercise was beneficial for response times across the morning following a high GI breakfast, whereas response times remained similar across the morning on the resting trial (figure 7.4a). These findings are similar to the findings presented in chapter VI, where exercise was also beneficial for adolescents’ response times across the morning, when compared with the resting trial. Upon inspection of figure 7.4a, it would appear that whilst response times were slower at 9.30 am on the exercise trial (before exercise) than at any other time on any other trial, they did improve across the morning following the mid-morning bout of exercise. Thus, the findings of the present study are consistent with those presented in chapter VI, showing a beneficial effect of a mid-morning bout of exercise on adolescents’ response times on the Sternberg paradigm, a test of working memory.
Overall, the findings of the present study suggest a beneficial effect of a low GI breakfast (regardless of exercise) and a mid-morning bout of exercise (following a high GI breakfast) for response times on the Sternberg paradigm. The present study is the first to examine their combined effects, but does suggest that either a low GI breakfast, or a mid-morning bout of exercise enhance response times on the Sternberg paradigm. However, the findings also suggest that by consuming a low GI breakfast and completing a mid-morning bout of exercise, there is no additional beneficial effect on response times above that achieved by either practice alone.

7.4.4: Mechanisms

The mechanisms mediating the effects of breakfast GI and a mid-morning bout of exercise on adolescents’ cognitive function were not directly examined in the present study. However, as with the other studies presented in this thesis, the measurement of blood glucose, plasma insulin and blood lactate concentrations allows speculation upon the mechanisms which may be responsible (see appendix D for comparison of blood glucose, plasma insulin and blood lactate concentrations following the high and low GI breakfasts). Both blood glucose (figure 7.5) and plasma insulin (figure 7.6) concentrations were higher following exercise, when compared with resting, following the high GI breakfast, but not following the low GI breakfast. However, despite the key role of glucose within the central nervous system (Dye et al, 2000), from the findings of the present study (suggesting a low GI breakfast is beneficial for cognitive function regardless of exercise, whereas the effects following a high GI breakfast can be dependent on exercise), it is clear that blood glucose concentrations are not the only determinant of cognitive performance. As speculated in
Chapter V, improvements in insulin sensitivity following a low GI breakfast may play a role (Schulze et al, 2004).

Furthermore, blood lactate concentrations were higher following the mid-morning bout of exercise, when compared with resting, following the low GI breakfast (and there was a tendency for a similar effect following the high GI breakfast) (figure 7.7). As speculated upon in chapter VI, it has been suggested that lactate may be oxidised by the brain (Schurr, 2006). However, it has also been suggested that lactate is only oxidised by the brain during hypoglycaemia (Maran et al, 1994), thus would not be oxidised by the brain in the present study. However, whilst it is not possible to suggest exact mechanistic pathways from the present study, the role of lactate is, at the very least, interesting and warrants further investigation. Also, as speculated upon in chapter VI, more general psychological and arousal mechanisms following a mid-morning bout of exercise may also affect cognitive function (Brisswalter et al, 2002).

7.4.5: Summary and Future Research Directions

The main findings of the present study are that the effects of breakfast GI and the mid-morning bout of exercise depend on the component of cognitive function being measured. For the Stroop test and Sternberg paradigm, response times improved across the morning following the low GI breakfast regardless of whether exercise was completed. However, following the high GI breakfast, exercise was beneficial for response times on the Sternberg paradigm, whereas response times improved across the morning on the resting trial on the Stroop test. In contrast, following the low GI breakfast, the magnitude of improvement in response times across the morning on the Stroop test was greatest on the exercise trial.
Across the components of cognitive function measured, response times seemed to be affected whilst accuracy was not, and these effects were only evident on the more complex levels of the tests employed, indicative of effects on more complex cognitive functions, whereas simpler tasks can be carried out to a similar level regardless of breakfast composition and exercise.

However, further work is required in this field to further examine the combined effects of breakfast composition and exercise on adolescents’ cognitive function. In everyday practice, both breakfast consumption and exercise (either during break times or physical education lessons) take place before or during the school morning, but the present study is the first to examine their combined effects. In addition, future work should also aim to examine: whether there is an optimal timing for breakfast and exercise during the morning; the effects of breakfasts with differing macronutrient contents; the effects of different modes, durations and intensities of exercise; as well as trying to establish the mechanisms responsible for such effects, within the ethical constraints of working with young people.
Chapter VIII

General Discussion

8.1: Overview of Key Findings

The experimental studies presented in the preceding four chapters of this thesis examined the effects of breakfast consumption, breakfast composition, and a mid-morning bout of exercise, on cognitive function in adolescent school children. The main findings are summarised below:

- Breakfast consumption was more beneficial for adolescents’ cognitive function than breakfast omission, in that accuracy (visual search and Stroop tests) and response times (Sternberg paradigm) were enhanced following breakfast consumption (chapter IV).

- Overall, consuming either the high or low GI breakfast was beneficial for response times and accuracy across the cognitive function tests, when compared with breakfast omission (chapter V).

- Consuming the low GI breakfast was more beneficial than consuming the high GI breakfast for adolescents’ cognitive function across the tests conducted (chapter V).

- The mid-morning bout of exercise following a self-selected breakfast was beneficial for adolescents’ performance on some tests of cognitive function (e.g. Sternberg paradigm), but did not affect performance on other tests (e.g. Stroop test) (chapter VI).

- The effects of the mid-morning bout of exercise were dependent upon breakfast GI and the component of cognitive function being examined (chapter VII). Specifically:
Following the high GI breakfast, the mid-morning bout of exercise was beneficial for response times on the Sternberg paradigm, whereas there was a greater improvement in response times across the morning on the resting trial on the Stroop test.

Following the low GI breakfast, the mid-morning bout of exercise did not confer any additional benefits to performance on the Sternberg paradigm, whereas on the Stroop test, response times improved across the morning on both the exercise and resting trials, with the magnitude of the improvement greatest on the exercise trial.

The following discussion analyses these points with respect to previous research in the area and evaluates any inferences for adolescents’ cognitive function across the school morning. The effects of breakfast consumption, breakfast composition and the mid-morning bout of exercise on each component of cognitive function will be considered. In addition, although not directly examined in this thesis, the mechanisms mediating any effects on adolescents’ cognitive function are discussed.

**8.2: Visual Perception**

In the studies presented in this thesis, visual perception was assessed by the visual search test. This section will discuss the effects of breakfast consumption, breakfast composition and exercise on visual perception in an adolescent population.
8.2.1: Breakfast Consumption vs. Breakfast Omission

Overall, the findings of the experimental studies presented in this thesis suggest that visual perception, as assessed by the visual search test, was enhanced following breakfast consumption, when compared to breakfast omission. In chapter IV, breakfast consumption was beneficial for accuracy, whereas in chapter V, a low GI breakfast was beneficial for both response times and accuracy, when compared to breakfast omission.

The finding that breakfast consumption enhances the accuracy of visual perception is in line with the findings of Mahoney et al (2005). The Mahoney et al (2005) study used the Rey complex figure copy and recall test as a test of visual perception and whilst the findings overall indicated a beneficial effect of breakfast consumption on visual perception, the authors suggested that both the age group of the children (6-8 and 9-11 year olds) and their sex, may have determined the effects of breakfast consumption on visual perception. Interestingly, the earlier study only found a beneficial effect on the accuracy of visual perception, whilst response times were unaffected (Mahoney et al, 2005). However, the findings presented in this thesis suggest a beneficial effect on both response times and accuracy on the visual search test. The variation in findings could be due to a number of factors, including differences in the age group studied and the tests of visual perception used.

It has already been suggested that adolescents are particularly worthy of study in this field for a number of reasons (see section 1.1.2), not least because they are undergoing puberty and thus their responses may be different to those of younger children and adults (Cromer et al, 1990; Kanarek, 1997). Therefore, given that the earlier study of Mahoney et al (2005) employed 6-11 year olds, whereas this thesis focussed on 12-15 year olds, the slight variation in findings is not surprising. Nonetheless, the studies presented in this thesis are the first to examine the effects of breakfast consumption on adolescents’ visual perception, with
the findings suggesting that breakfast consumption, as opposed to breakfast omission, is beneficial for performance on the visual search test.

8.2.2: Breakfast Composition

The findings of the experimental studies presented in this thesis suggest that the low GI breakfast was more beneficial than the high GI breakfast, for both response times and accuracy on the visual search test. Interestingly, the findings of chapter V also suggested that breakfast omission may actually have been more beneficial than the high GI breakfast for visual perception in adolescents, when participants were resting throughout the morning.

The effects of breakfast GI on visual perception in adolescents have not previously been examined. However, the effects of a high GI breakfast, a low GI breakfast and breakfast omission on visual perception have been examined in 6-8 and 9-11 year olds (Mahoney et al, 2005). In 6-8 year old males, the accuracy of visual perception was enhanced following a high GI breakfast when compared to breakfast omission, whereas in 6-8 year old females the accuracy of visual perception was enhanced following breakfast omission when compared to following a high GI breakfast (Mahoney et al, 2005). The findings in the 6-8 year old females are in line with those in adolescents presented in this thesis, suggesting breakfast omission was more beneficial than a high GI breakfast for visual perception, when participants were resting throughout the morning.

However, in the 9-11 year olds, the accuracy of visual perception was greater following both the high and low GI breakfasts when compared to following breakfast omission (Mahoney et al, 2005). These findings are, at least, partly in accordance with the findings presented in this thesis, suggesting a beneficial effect of the low GI breakfast for
visual perception. However, these comparisons and those in the previous paragraph, between the experimental studies described in this thesis and the study of Mahoney et al (2005) are limited due to the differences in the age groups studied, the breakfasts provided and the tests of visual perception employed. However, the studies presented in this thesis add to the existing literature by examining the effects of breakfast GI on visual perception in an adolescent population, with the findings suggesting the low GI breakfast was beneficial for adolescents’ visual perception, whereas the high GI breakfast may have been detrimental, even when compared with breakfast omission, when participants were resting throughout the morning.

8.2.3: Exercise

The findings of chapter VI suggest that, on the complex level of the visual search test, a speed-accuracy trade-off was evident following exercise, whereby participants responded quicker, but as a result also become less accurate following the mid-morning bout of exercise. However, the same effect was not seen following either the high or low GI breakfast in chapter VII, where the mid-morning bout of exercise did not affect response times or accuracy on the visual search test.

The effects of exercise on subsequent visual perception in adolescents have not been previously examined and thus the studies presented in this thesis are the first to document these effects. In their meta-analysis, which included data from 4-18 year olds, Sibley & Etnier (2003) found that perceptual skills showed the largest effect size (ES = 0.49), indicative of a large, positive effect of exercise on perceptual skills. However, these data were drawn from five unpublished studies conducted across a large age range, making it
difficult to draw conclusions regarding the effects of exercise on adolescents’ perceptual skills.

In addition to the above work in children, a single bout of exercise has been shown to be beneficial for response times on a test of visual perception, in adults who were experts in decision making sports (Davranche & Audiffren, 2004). This improvement in response times is similar to that seen in chapter VI, but the concurrent decrease in accuracy was not seen in the earlier study (Davranche & Audiffren, 2004). The authors suggest the improvement in response times may have been due to increases in arousal (Davranche & Audiffren, 2004). In the adolescents tested in the present studies, should exercise have increased arousal (and the effects were still evident 45 min later), it appeared to cause adolescents to trade-off accuracy for speed in the findings reported in chapter VI, whilst having no effect in the findings reported in chapter VII. Therefore, whilst the studies presented in this thesis add to the existing literature by examining an adolescent population, it appears the effects of a mid-morning bout of exercise on adolescent’s visual perception are unclear, and thus require further investigation.

8.2.4: Summary for Visual Perception

Overall, the studies presented in this thesis suggest that breakfast consumption was more beneficial than breakfast omission for adolescents’ visual perception. Furthermore, the consumption of a low GI breakfast was shown to be particularly beneficial for both response times and accuracy on the visual search test, with some evidence to also suggest that breakfast omission may actually have been more beneficial than consumption of a high GI breakfast, when participants were resting throughout the morning. Finally, the mid-morning
bout of exercise caused a speed-accuracy trade-off in the findings reported in chapter VI, whereby participants responded quicker, but as a result became less accurate following exercise, though this effect was not evident following either the high or low GI breakfasts in the findings reported in chapter VII. Thus, the exact effects of exercise on adolescents’ visual perception remain unclear and warrant further investigation.

8.3: Attention

In the studies presented in this thesis, (selective) attention was assessed by the Stroop test (chapters IV – VII) and Flanker task (chapter V). This section will discuss the effects of breakfast consumption, breakfast composition and exercise on attention in an adolescent population.

8.3.1: Breakfast Consumption vs. Breakfast Omission

In the present thesis, the effects of breakfast consumption on attention were assessed via the Stroop test (chapter IV and chapter V) and the Flanker task (chapter V). The findings reported in both chapters suggest that breakfast consumption was beneficial for attention in adolescents, when compared to breakfast omission. Specifically, the findings reported in chapter IV breakfast consumption was beneficial for accuracy on the Stroop test, whereas in the findings reported in chapter V, a low GI breakfast was beneficial for response times when compared to breakfast omission on both the Stroop test and Flanker task. In addition, a low GI breakfast was also beneficial for accuracy on the Flanker task. The findings presented in this thesis therefore clearly suggest a beneficial effect of breakfast consumption on attention
in adolescents, an argument given extra support by the consistency of the effects across both the Stroop test and Flanker task.

The effects of breakfast consumption on attention in adolescents was examined in an early cross-sectional study, with the findings indicating no differences in attention between habitual breakfast consumers and those who regularly omitted breakfast (Dickie & Bender, 1982). However, due to the cross-sectional nature of the study, a number of confounding variables may have influenced study outcomes, meaning causal relationships between breakfast consumption and attention are very difficult to establish. However, more recently, in 9-11 year olds, it was suggested, in line with the findings presented in this thesis, that breakfast consumption was beneficial for the accuracy of attention, when compared to breakfast omission (Mahoney et al, 2005). However, the studies presented in this thesis are the first to use a cross-over study design to examine the effects of breakfast consumption on attention in adolescents, with the findings suggesting a beneficial effect on performance of both the Stroop test and Flanker task, when compared to breakfast omission.

8.3.2: Breakfast Composition

The findings of the experimental studies presented in this thesis suggest that a low GI breakfast is more beneficial than a high GI breakfast for attention in adolescents. Specifically, the findings presented in chapter V suggest that both response times and accuracy on the Stroop test and Flanker task were enhanced following the low GI breakfast when compared to following the high GI breakfast. Furthermore, the findings presented in chapter VII suggest there was an improvement in response times across the morning on the Stroop test following
the low GI breakfast regardless of exercise, whereas the same effects were not evident following the high GI breakfast.

Two earlier studies have also examined the effects of the GI of breakfast on adolescents’ performance on the Stroop test, with results indicating that a high GI breakfast was more beneficial than a low GI breakfast, but only in the group who had consumed a high glycaemic load (GL) breakfast (Micha et al, 2008). However, it has also been reported that neither the GI nor GL of breakfast affects adolescents’ performance on the Stroop test (Micha et al, 2010). It must be considered however that the earlier studies suffered from a number of methodological weaknesses, including; providing high and low GL meals that were not matched for energy content, not reporting whether response times and/or accuracy were assessed on the Stroop test and furthermore, not employing a crossover design, with participants consuming only the high or low GL breakfasts (Micha et al, 2008; Micha et al, 2010). In comparison, in the experimental studies in the present thesis, participants performed all trials in a randomised crossover design and the breakfasts were matched on key variables such as energy and macronutrient content.

In accordance with the findings presented in this thesis, previous studies have shown beneficial effects of a low GI breakfast on other tests of attention. For example, 6-7 year olds displayed fewer lapses in attention (as assessed by classroom behaviour) following a low GI breakfast compared to following a high GI breakfast (Benton et al, 2007). Furthermore, using a digit vigilance task, the findings of Wesnes et al (2003) suggest that the declines in attention seen following a high GI breakfast were reduced following a low GI breakfast in 9-16 year olds. However, these earlier studies did not focus specifically on an adolescent population (Wesnes et al, 2003; Benton et al, 2007).
By contrast, the studies presented in this thesis focus specifically on an adolescent population and use counterbalanced, cross-over designs, and provide high and low GI breakfasts matched on key variables (i.e. energy and macronutrient content), allowing greater claims to be made regarding the causality between breakfast GI and attention in adolescents. Furthermore, the beneficial effects of the low GI breakfast are seen consistently across two tests of attention (Stroop test and Flanker task) and the findings presented in chapter VII confirm that the beneficial effects of the low GI breakfast remain following exercise, as shown by improvements in response times across the morning on the Stroop test, an effect not seen following the high GI breakfast.

8.3.3: Exercise

The findings presented in this thesis suggest an inconsistent effect of the mid-morning bout of exercise on adolescents’ attention, as assessed by the Stroop test. Specifically, in the study reported in chapter VI there was a tendency for an improvement in response times following exercise on both test levels, though this did not reach statistical significance. In the findings reported in chapter VII, the mid morning bout of exercise was beneficial for response times on the complex level of the Stroop test following the low GI breakfast, whereas following the high GI breakfast there was a greater improvement in response times across the morning on the resting trial, suggesting that the effects of the mid-morning bout of exercise were dependent upon breakfast GI.

The evidence from the literature also appears to be mixed regarding the effects of exercise on attention. The present studies are the first to examine the effects of a mid-morning bout of exercise on adolescents’ performance of the Stroop test, but previous studies
have used the Flanker task as a test of attention (Hillman et al, 2009; Stroth et al, 2009). In an adolescent population, Stroth et al (2009) found no beneficial effect of exercise on response times or accuracy on the Flanker task. Contrary to these findings, in 9-10 year olds, exercise led to an improvement in accuracy on the Flanker task (Hillman et al, 2009). However, Hillman et al (2009) employed pre-adolescent children and tested 25 min after exercise using the Flanker task, whereas the present study focused on adolescents and the Stroop test was completed 45 min after exercise, thus potentially explaining the variation in findings. Clearly, there is ambiguity in the literature regarding the effect of exercise on adolescents’ attention, but the studies presented in this thesis suggest exercise may be beneficial for adolescents’ attention, but that this effect is affected by the GI of the breakfast consumed before the exercise.

8.3.4: Summary for Attention

Overall, the studies presented in this thesis suggest that breakfast consumption was more beneficial than breakfast omission for adolescents’ attention. Furthermore, the consumption of a low GI breakfast was more beneficial than both a high GI breakfast and breakfast omission for adolescents’ attention, an argument given extra weight by the consistency of the effects across both the Stroop and Flanker tasks. However, the effects of the mid-morning bout of exercise were not as clear, and were dependent upon the breakfast GI, in that the mid-morning bout of exercise was beneficial following the low GI breakfast, but not following the high GI breakfast.
8.4: Working Memory

In the studies presented in this thesis, working memory was assessed by the Sternberg paradigm. Based upon the multi-component model proposed by Baddeley & Hitch (1974), working memory consists of two subsidiary storage systems (the phonological loop and visuospatial sketchpad) and the central executive. Primarily, working memory tasks such as the Sternberg paradigm assess the central executive, which is the most important, but least understood, component of working memory (Baddeley, 2003). Miyake et al (2000) have suggested that the central executive consists of separable but related functions performed by the frontal lobes (Miyake et al, 2000), which act as the control system within the working memory model (Baddeley, 2003).

The following section will discuss the effects of breakfast consumption, breakfast composition and exercise on working memory (as assessed by the Sternberg paradigm) in an adolescent population.

8.4.1: Breakfast Consumption vs. Breakfast Omission

Overall, the findings of the studies presented in this thesis suggest a beneficial effect of breakfast consumption, when compared to breakfast omission, on working memory (as assessed by the Sternberg Paradigm). Specifically, in the findings reported in chapter IV, breakfast consumption was beneficial for response times on the Sternberg paradigm, when compared to breakfast omission. Furthermore, in the study reported in chapter V, consumption of the low GI breakfast was more beneficial than breakfast omission for accuracy on the Sternberg paradigm.
It has previously been suggested, in line with the findings presented in this thesis, that breakfast consumption is beneficial for memory processes in young people, when compared to breakfast omission (Pollitt & Matthews, 1998). However, the authors of the review paper stressed that these were tentative conclusions and that further work should be conducted in adolescent populations, a void in the literature partly addressed by the studies presented in this thesis.

A number of early studies also examined the effects of breakfast consumption on memory processes in adolescents, with some findings suggesting no beneficial effect of breakfast consumption on working memory function (as assessed by a sentence verification task (Dickie & Bender, 1982) and the Rey Auditory Visual Learning test (Cromer et al, 1990)). However, more recently, it has also been suggested that breakfast consumption was beneficial for the accuracy of visuospatial memory (Widenhorn-Müller et al, 2008). However, comparisons with the findings of this thesis are difficult due to the slightly different age groups of the populations tested, the different components of memory measured and the tests used to assess these components of memory (Dickie & Bender, 1982; Cromer et al, 1990; Widenhorn-Müller et al, 2008). The present thesis does however, partly address the void in the literature highlighted by Pollitt & Matthews (1998), with the findings suggesting that, overall, breakfast consumption is beneficial for working memory in adolescents (as assessed by the Sternberg Paradigm), when compared to breakfast omission.

**8.4.2: Breakfast Composition**

The findings of the experimental studies presented in this thesis suggest that the low GI breakfast was more beneficial than the high GI breakfast for working memory (as assessed
by the Sternberg Paradigm) in adolescents. Specifically, in chapter V the findings suggest the low GI breakfast is more beneficial for both response times and accuracy on the Sternberg Paradigm, when compared to following the high GI breakfast. Furthermore, in the findings reported in chapter VII, response times on the Sternberg Paradigm improved across the morning following the low GI breakfast regardless of exercise, whereas the same effects were not evident following the high GI breakfast.

The findings of an earlier study conducted in 9-16 year olds suggests, in line with the findings presented in this thesis, that a low GI breakfast was more beneficial than a high GI breakfast for the speed of working memory (Wesnes et al, 2003). However, in the earlier study, the accuracy of working memory was not investigated, thus the beneficial effects on accuracy seen in the present thesis cannot be compared with the earlier study (Wesnes et al, 2003). The accuracy of working memory was examined however, in the study of Mahoney et al (2005), with the findings suggesting accuracy was enhanced following a low GI breakfast compared to following a high GI breakfast, but this was only seen in 9-11 year old females.

Therefore, the studies presented in this thesis add to the existing literature by being the first to examine the effects of breakfast GI on both the speed and accuracy of working memory in an adolescent population. The findings suggest that the low GI breakfast was beneficial for both response times and accuracy, when compared to the high GI breakfast. Furthermore, the findings presented in chapter VII also suggest that the beneficial effects of the low GI breakfast are not affected by exercise, with an improvement in response times seen regardless of exercise, an effect not seen following the high GI breakfast.
Chapter VIII: General Discussion

### 8.4.3: Exercise

The findings presented in this thesis suggest a beneficial effect of a mid-morning bout of exercise on the speed of adolescents’ working memory (as assessed by the Sternberg paradigm). Specifically, in the findings reported in chapter VI, the mid-morning bout of exercise resulted in an improvement in response times across the morning on the Sternberg paradigm. Furthermore, in the findings reported in chapter VII, the mid-morning bout of exercise enhanced response times across the morning on the Sternberg paradigm, but this was only evident following the high GI breakfast (response times improved across the morning regardless of exercise following the low GI breakfast). Overall, the findings of this thesis suggest that a mid-morning bout of exercise is beneficial for the speed of adolescents’ working memory, but following the low GI breakfast (in chapter VII) the mid-morning bout of exercise did not confer any additional benefits.

The studies presented in this thesis are the first to examine the effects of a mid-morning bout of exercise on working memory in adolescents. Interestingly, in the meta-analysis of Sibley & Etnier (2003), memory was the only component of cognitive function not affected by exercise in 4-18 year olds (ES = 0.03). However, as previously stated, comparisons between the present studies and those in the meta-analysis must be made cautiously due to the different age groups examined and no details being provided regarding the mode, duration and intensity of exercise in the unpublished studies included in the meta-analysis, or the timing of the cognitive tests relative to the exercise.

The studies presented in this thesis are the first to examine the combined effects of breakfast GI and exercise on adolescents’ working memory, and the findings indicated that the effects of the exercise were dependent upon breakfast GI. Previous research, in accordance with the findings presented in this thesis (chapter V), has shown that a low GI
breakfast is beneficial for adolescents working memory, when compared to a high GI breakfast (Wesnes et al, 2003). However, the work presented in this thesis extends current knowledge by showing that whilst a mid-morning bout of exercise did not confer any additional benefits to the consumption of a low GI breakfast (response times improved across the morning on both the exercise and resting trials), the mid-morning bout of exercise was beneficial for response times following the high GI breakfast.

In conclusion, the studies presented in this thesis suggest a beneficial effect of a mid-morning bout of exercise on response times on the Sternberg paradigm, indicative of a greater speed of working memory. However, it must also be noted that this effect was dependant on the breakfast GI. Given that no previous studies have examined the effects of exercise on adolescents’ working memory, the present studies add to the existing literature by documenting these effects.

8.4.4: Summary for Working Memory

Overall, the studies presented in this thesis suggest that breakfast consumption, the low GI breakfast, and the mid-morning bout of exercise, were all beneficial for working memory in adolescents, when compared to breakfast omission, a high GI breakfast, and continuing to rest, respectively. However, the effects of exercise were dependent upon breakfast GI, in that exercise was beneficial for response times following a high GI breakfast, but did not confer any additional benefit following consumption of the low GI breakfast.
8.5: Mechanisms

The mechanisms mediating the effects of breakfast consumption, breakfast GI and a mid-morning bout of exercise on adolescents’ cognitive function were not directly investigated in the studies presented in this thesis. However, through the measurement of mood and blood glucose, plasma insulin and blood lactate concentrations, speculation upon the mechanisms responsible is possible.

The enhanced cognitive function seen following breakfast consumption, as opposed to breakfast omission, was combined with improvements in mood and higher blood glucose concentrations (chapter IV). Indeed, it has previously been suggested that as glucose is the only metabolite that can be used by the central nervous system, higher blood glucose concentrations are associated with enhanced cognitive performance (Dye et al, 2000). Whilst the exact mechanisms by which increased glucose concentrations improve cognitive function are unknown, one potential explanation is increased synthesis of acetylcholine by the cholinergic system (Owens & Benton, 1994).

However, blood glucose concentrations are not the only mechanism mediating the effects of breakfast composition on cognitive function. This is evidenced by the enhanced cognitive performance following the low GI breakfast, despite higher blood glucose and plasma insulin concentrations following the high GI breakfast (chapter V). Therefore, whilst glucose may be key in determining cognitive performance between the fed and fasted states (chapter IV), glucose concentrations (within the normal postprandial range) do not seem to predict cognitive performance following breakfasts of different compositions. As suggested in the discussion of chapter V (section 5.4.2), other factors such as improved insulin sensitivity following the low GI breakfast may also play a role in determining such cognitive performance (Schulze et al, 2004). Furthermore, the findings of Warren et al (2003) indicate
that adolescents’ hunger and subsequent energy intake at lunch was significantly lower following a low GI compared to following a high GI breakfast. Interestingly, the findings of Warren et al (2003) also indicate that satiation immediately following the high and low GI breakfasts was not different, consistent with the findings of the studies presented in this thesis. However, greater gut fullness and satiety later in the morning could be a contributory mechanism to the enhanced cognitive function following the low GI breakfast.

The studies examining the effects of exercise on adolescents’ cognitive function also add weight to the view that glucose availability is not the sole determinant of cognitive function. Blood glucose and plasma insulin concentrations were increased following exercise (chapter VI and following the high GI breakfast in chapter VII), though the effects on cognitive function depended upon the component being measured. Blood lactate concentrations were also higher following the mid-morning bout of exercise, though the role of lactate within the brain and its effects on cognitive function are not well understood. It has been suggested that the brain may oxidise lactate as a metabolic fuel (Schurr, 2006), whilst other authors have suggested that the brain will only oxidise lactate under conditions of hypoglycaemia (Maran et al, 1994). A recent review indicated that lactate may contribute approximately 7% to cerebral energy requirements at rest, which may increase to 25% during exercise, when blood lactate concentrations reach 7 mmol.L⁻¹ (van Hall, 2010). However, the effects of such oxidation of lactate in the brain on cognitive function are not well understood, and in the studies presented in this thesis, blood lactate concentrations were much lower than the 7 mmol.L⁻¹ suggested by van Hall et al (2010), thus lactate oxidation is unlikely to have contributed to the observed differences in cognitive function.

In addition, a number of other mechanisms mediating the effects of exercise on cognitive function have been suggested. These include: increased cerebral blood flow
resulting in enhanced delivery of glucose and oxygen to, and removal of waste products from, the brain (Jorgensen et al, 2000); increased arousal (Brisswalter et al, 2002); and more efficient signalling within the brain (Hillman et al, 2009; Stroth et al, 2009). Furthermore, should insulin sensitivity play a role in determining cognitive function (due to greater glucose uptake across the blood brain barrier), the enhanced insulin sensitivity following exercise (Borghouts & Keizer, 2000) could also be responsible for affecting cognitive function.

Overall, whilst exact mechanistic claims are not possible from the studies presented in this thesis, speculation upon the potential mechanisms mediating the effects on adolescents’ cognitive function is possible. It appears from the findings of chapter IV (and the available literature) that glucose availability is a key determinant of cognitive function between the fed and fasted states. However, whilst many mechanisms mediating the effects of breakfast GI and a mid-morning bout of exercise have been suggested, exact mechanisms remain unclear and certainly warrant further investigation.

8.6: Conclusions Concerning: the relative importance of breakfast and exercise; the time course of the effects; task complexity; and whether response times and/or accuracy are affected

Throughout the studies presented in this thesis, several patterns have emerged where beneficial effects on cognitive function have been observed. Specifically:

- *The relative importance of breakfast and exercise:* The results presented in this thesis clearly suggest that breakfast consumption (particularly a low GI breakfast) is beneficial for adolescents’ cognitive function. However, the effects of exercise are more variable. In
addition, as evidenced by the findings reported in chapter VII, the effects of completing the mid-morning bout of exercise appear to be dependent upon the breakfast GI. Overall the nutritionally induced effects (following breakfast consumption and a low GI breakfast) are more consistent than the exercise induced effects. However, breakfast consumption, a low GI breakfast, and exercise, all have well documented health benefits (e.g. Pearson et al, 2009; Livesey et al, 2008; Berlin & Colditz, 1990); thus taken together with their positive effects (or at least null effects) on cognitive function, they are all behaviours that should be promoted among adolescents, both for physical health and cognitive function.

- **The time course of the effects:** The beneficial effects of breakfast consumption and, in particular, a low GI breakfast become more apparent later in the school morning, presumably once the breakfast has been digested and absorbed. These findings suggest that breakfast habits could therefore affect cognitive function (and consequently academic achievement) across the whole of the school morning. The effects of exercise were only examined later in the morning, as the exercise was not completed until mid-morning. Therefore, the exact time course of the effects remains unknown, but the present studies add to the existing literature by examining cognitive function 45 min post exercise, with previous literature focussing on the more immediate effects.

- **Task complexity:** Across the studies presented in this thesis, the beneficial effects of breakfast and/or exercise tended to only be evident on the more complex levels of the cognitive function tests. This suggests that the beneficial effects were specific to the cognitive functions examined, rather than just simple information processing effects (as examined by the baseline levels of the cognitive function tests). The simpler, baseline, levels tended to be completed to a similar level regardless of breakfast consumption, breakfast composition and a mid-morning bout of exercise, whereas such factors affected performance on the more complex, cognitively demanding tasks.
**Response times or accuracy?** In this thesis, the experimental studies examined both response times and accuracy across the cognitive function tests, an advance on many previous studies in the area which examined only one variable. Both response times and accuracy were examined to investigate the possibility of speed-accuracy trade-offs (e.g. the visual search test in chapter VI). The findings suggest that whilst breakfast consumption (particularly a low GI breakfast) was beneficial for both response times and accuracy (chapters IV and V), a mid-morning bout of exercise only appeared to affect response times (chapters VI and VII).

It is also interesting to note that it has been suggested that adults will slow down to preserve accuracy (thus effects will be seen on response times), whereas children (4-13 years old) will maintain a more constant response speed, but this will be to the detriment of accuracy (thus effects will be seen on accuracy) (Davidson et al, 2006). Interestingly, in the present studies, adolescents (11-15 years old) appear to exhibit a developmental stage, whereby both response times and accuracy may be affected.

### 8.7: Recommendations for Future Research

In light of the findings presented in this thesis and the available literature, the following studies would add to present knowledge regarding the factors determining adolescents’ cognitive function:

1. A series of investigations into the time course of the effects of breakfast consumption, breakfast composition and exercise on cognitive function in adolescents (i.e. for how long are the beneficial effects evident after breakfast consumption and/or exercise?)
2. An investigation into the effects of breakfasts with different macronutrient contents on cognitive function in adolescents. For example, comparison of a high fat as opposed to a high carbohydrate breakfast.

3. Where possible, given the ethical constraints of working with young people, an investigation into the effects of exercise following breakfast omission on cognitive function in adolescents.

4. A series of investigations into the effects of different exercise intensities, modes and durations on cognitive function in adolescents.

5. Further investigation into the mechanisms mediating the nutritional and exercise induced effects on cognitive function. Studies must consider the ethical constraints of working with young people, but where possible, capillary blood samples should be taken and brain imaging techniques used, to try and establish the mechanisms mediating the effects upon adolescents’ cognitive function.

Furthermore, it is important that the above studies are conducted focusing on an adolescent population, measuring specific components of cognitive function (using tests that are suitable for adolescents), and measure both response times and accuracy, to ensure that any observed effects are not due to speed-accuracy trade-offs.


References


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# List of Appendices

## Appendix A

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## Appendix D

Comparison between the high and low GI breakfasts:

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Dear Parent/Guardian/Care-Giver,

Your child’s school has agreed to participate in some research work being carried out by the School of Sport and Exercise Sciences and the Institute of Youth Sport at Loughborough University. This research aims to examine the effect of breakfast on the cognitive function of young people during the school morning. The term ‘cognitive function’ refers to a range of measures which influence the ability of young people to learn at school, including variables such as memory (the ability to retain information) and attention (the ability to concentrate over a period of time). Ultimately, the research may allow recommendations as to the ‘optimum’ breakfast which should be consumed by young people to optimise learning during the school morning.

As part of this project, we are looking to recruit pupils from your child’s school. In order to participate, your child would complete one familiarisation session and two main trials. The familiarisation session is to introduce your child to the purpose of the study and allow them to try out the tests that will form the main trials. During this time, simple measures of height, weight and waist circumference will be taken and a short questionnaire on your child’s breakfast habits completed.

During the main trials (which will be scheduled one week apart), your child will be asked to come to school without breakfast. On one trial breakfast will be provided immediately upon arrival at school, whereas on the other trial breakfast will be provided upon completion of the tests (at approximately 10.30am). On each trial, your child will complete a series of computer based cognitive tests and a mood questionnaire, shortly after arrival at school and again 2 hours later. Each child will also be asked to complete a 24 hour dietary recall. For one week between main trials, we will provide your child with a pedometer (a small device to count the number of steps taken over the course of the day) and ask that they record any physical activity undertaken during this period. In addition, some children will have a small finger-prick
blood sample taken, which will be analysed for blood glucose concentration. Please note the separate section on the informed consent form for you to indicate if you are willing for your child to participate in this test.

In this pack you should find:

1. An information sheet, explaining in greater detail the purpose and requirements of each of the tests mentioned above.
2. An informed consent form, which must be signed by you and returned to the school before your child can participate in the study.
3. A health screen questionnaire, for you to complete in conjunction with your child – this is to make us aware of any medical conditions relating to your child.

All procedures for this study have been approved by Loughborough University’s Ethical Advisory Committee. Your child is under no obligation to participate in the study and it will be made clear that they can withdraw at any time, or only participate in some elements of the study, without providing a reason. All data will be kept in the strictest confidence and stored anonymously.

We do hope that your child and the rest of their class participate in the study, which not only provides them with a learning experience outside of the classroom but will also provide them with a measure of their physical activity levels. If you are willing for your child to participate in the study, please complete the enclosed informed consent form and health screen questionnaire and return to the school.

If you have any questions regarding the study, please do not hesitate to contact the staff responsible:
Simon Cooper at S.B.Cooper@lboro.ac.uk or call 07788170208, or Dr Mary Nevill at M.E.Nevill@lboro.ac.uk or call (01509) 226315, or Dr Stephan Bandelow at S.Bandelow@lboro.ac.uk or call (01509) 223009.

Yours sincerely,

Dr Mary Nevill (Director of the Institute of Youth Sport)
Background Information
It is often stated that breakfast is the most important meal of the day, but research suggests it is commonplace for many people, especially young people, to skip breakfast. Your child’s school has agreed to participate in this research project, conducted by the School of Sport and Exercise Sciences and the Institute of Youth Sport at Loughborough University. The study aims to investigate the effects of breakfast on the cognitive function of young people. Cognitive function includes many variables such as memory and attention and is believed to be affected by skipping breakfast. If breakfast consumption can positively affect these measures, there is a potential benefit for academic performance, allowing your child to perform better at school.

Screening
Prior to your child participating in the study, we ask you to complete a health screen questionnaire about them. This is to ensure that your child has no health problems that could prevent them from participating in the study.
In addition, on each testing day, your child will be asked if they are free from illness before participation.

What your child will be asked to do:
+ The first stage will be to familiarise your child with the measures to be conducted. During this time, simple measures of height and weight will be taken, along with a measure of waist circumference. We will also ask your child to complete a short questionnaire on their usual breakfast habits.
+ Each child will then complete two main trials (scheduled one week apart). On one trial, breakfast will be provided upon arrival at school and on the other, it will be provided upon completion of the tests (at approximately 11am).
+ During each trial, the cognitive function tests and a mood questionnaire will be completed shortly after arrival at school and again 2 hours later. We will also ask your child to complete a simple 24 hour dietary recall.
+ In the week between main trials, we will ask your child to wear a pedometer, a small device to count the number of steps taken over the course of the day. In combination with this, we ask your child to record any physical activity they undertake during this period on the sheet provided.
+ A small number of children will also have a finger prick blood sample taken: this will be analysed for glucose concentration. Please note this will take place in only some subjects and there is a separate section on the informed consent form for you to indicate whether you are willing for your child to take part in this test. Non-participation in this element of the study DOES NOT affect participation in the other tests.
Assessment of Dietary Habits
The aim of the 24 hour dietary recall is to get an idea of your child’s dietary patterns. An investigator will ask your child to recall all food and drink consumed over the past 24 hours. However, please note:

Your child should not eat anything from 10pm the evening before each main trial, but may drink water freely during this time.

If this has not been possible, please inform the investigators upon arrival at school.

Breakfast
The breakfast provided will consist of cereals and orange juice. Depending on which trial your child is undertaking, breakfast will be served either upon arrival at school or following completion of the testing, at approximately 11am. Please let us know on the enclosed informed consent sheet of any special dietary requirements your child has.

Cognitive Function Tests/Mood Questionnaire
The cognitive function tests are completed via a laptop computer shortly after arrival at school and again 2 hours later. Each testing session will last 15-20 minutes and will provide measures of your child’s cognitive function at that time, including indicators of working memory, visual search and attention. The mood questionnaire asks your child to indicate how they feel on various measures on a scale of 1 to 5, e.g. how ‘relaxed’ do you feel now?

Blood Glucose
A small finger prick blood sample will be taken and analysed for glucose concentration. This involves minimal discomfort for your child. Please remember to indicate on the consent form whether you are willing for your child to participate in this test. Non-participation in this element of the study DOES NOT affect participation in the other tests.

Pedometer/Physical Activity Measures
A pedometer is a small device worn on a belt around the waist. It counts the total number of steps taken. Your child will be asked to wear the pedometer for one week between main trials, taking note at the end of each day of the number of steps taken. The pedometer does not interfere with normal daily activities and will be similar to the one below:

We will also provide a simple, easy to use sheet, for your child to record any physical activity they undertake, over the duration of the pedometer use. Further instructions are provided on the sheet.
Important Notes

- Although these tests take place at school, it is NOT compulsory for your child to take part.
- Your child can withdraw from the study at any time without providing a reason.
- All staff involved in the study undertake training in the measures involved and undergo a CRB check to clear them to work with children.
- All information will be stored anonymously and no individual data will be reported in the findings of the study.
- The study has been approved by Loughborough University’s Ethical Advisory Committee.

Benefits of the Study

✓ The overall aim of this study is to assess the effect of breakfast on the cognitive function of young people during the school morning. Ultimately, recommendations can be made regarding breakfast consumption to optimise young peoples learning at school.
✓ In addition to these long term benefits, your child will receive a measure of their physical activity levels through the pedometer and information as to whether they are achieving the national target of 12,000 steps per day.

What to do now

If you are willing for your child to participate in the study, please complete the enclosed consent form and health screen questionnaire and return to your child’s school.

Contact Details

If you have any questions or concerns regarding the study please do not hesitate to contact the staff responsible for the study:
Simon Cooper at S.B.Cooper@lboro.ac.uk or call 07788170208
OR Dr Mary Nevill at M.E.Nevill@lboro.ac.uk or call (01509) 226315
OR Dr Stephan Bandelow at S.Bandelow@lboro.ac.uk or call (01509) 223009.
A2: Informed Consent Form

Breakfast and Cognition

Parent / Guardian / Care-Giver Consent

I have been given the opportunity to ask questions (contact details of study staff below) and I understand what is required from my child.

I understand that the study has been approved by Loughborough University’s Ethical Advisory Committee.

I have seen the information sheet and fully understand what the following measurements entail:
- Cognitive function tests
- Mood questionnaire
- Finger prick blood samples
- Height, body mass and waist circumference

Dietary Requirements

Please indicate if your child has any special dietary requirements that we should be aware of:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

Consent

Child’s Name: ........................................... D.O.B.: .................

Contact Name: ...........................................

Contact Telephone Number: ..............................
(We will use the above details to contact you regarding your child’s participation in the study)

I give permission for my child to participate in the breakfast and cognition study.

Signed (parent/guardian): ...........................................

Print Name (parent/guardian): ...........................................

Date: .....................

Contact Details
Dr Mary Nevill: M.E.Nevill@lboro.ac.uk or (01509) 226315
Dr Stephan Bandelow: S.Bandelow@lboro.ac.uk or (01509) 223009
Simon Cooper: S.B.Cooper@lboro.ac.uk or 07788170208
Maria Nute: M.L.Nute@lboro.ac.uk or (01509) 226381.
As a volunteer participating in a research study, it is important that your child is currently in good health and has had no significant medical problems in the past. This is (i) to ensure their continued well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

If your child has a blood-borne virus, or thinks that they may have one, they should not take part in the blood glucose tests in this study.

Please complete this brief questionnaire to confirm your child’s fitness to participate:

1. **At present**, does your child have any health problem for which they are:
   - (a) on medication, prescribed or otherwise
   - (b) attending their general practitioner
   - (c) on a hospital waiting list

2. **In the past two years**, has your child had any illness which required them to:
   - (a) consult their GP
   - (b) attend a hospital outpatient department
   - (c) be admitted to hospital

3. **Has your child ever** had any of the following:
   - (a) Convulsions/epilepsy
   - (b) Asthma
   - (c) Eczema
   - (d) Diabetes
   - (e) A blood disorder
   - (f) Head injury
   - (g) Digestive problems
   - (h) Heart problems
   - (i) Problems with bones or joints
   - (j) Disturbance of balance/co-ordination
   - (k) Numbness in hands or feet
   - (l) Disturbance of vision
   - (m) Ear/ hearing problems
   - (n) Thyroid problems
   - (o) Kidney or liver problems
   - (p) Allergy to nuts

4. **Has any**, otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise?

If YES to any question, please describe briefly if you wish (e.g. to confirm problem was/is short-lived, insignificant or well controlled.)
A4: Willingness to Participate Form

Breakfast and Cognitive Function

WILLINGNESS TO PARTICIPATE FORM

The purpose and details of this study have been explained to me.

I understand that this study is designed to further understanding of the effect of exercise on cognitive function in young people.

I understand that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation in this study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and all records made will not use my name and therefore all results will be anonymous.

I am willing to participate in this study.

Name: ........................................................................................................

Signature: ..............................................................................................

Signature of Researcher: .................................................................

Date: .................................................................................................
B1: Visual Search Test

*Baseline Level*

Please press the space bar as soon as you see a triangle, like in the examples below.

Press the space bar to start the test.

△ △ △ △ △
Please press the space bar as soon as you see a triangle, or just a few points of a triangle, like in the examples below.

Press the space bar to start the test.
B2: Stroop Test

Baseline Level

Quickly choose the word that matches the word on center screen. Use the arrow keys to select between the two choices on either side of the large word in the center. We will begin with 6 practice runs.

Press space to begin.
Complex Level

Quickly choose the colour in which the word on center screen is written, rather than the colour that the word names. Most people find this level the hardest. You probably will take more time for each word, and may frequently make the mistake of choosing the word itself, rather than the colour in which the word appears. Use the arrow keys to select between the two choices on either side of the large word in the center. We will begin with 6 practice runs.

Press space to begin.
B3: Sternberg Paradigm

e.g. Five-Letter Level

You can see 5 red letters on the next line: J H P O X

Please try to remember these letters. During the test, letters will appear. Every time you see one of the letters shown above, please press the right arrow key. With all other letters, press the left arrow key. We will do a practice session with 6 trials first.

Press space to begin.
B4: Flanker Task

Focus on the central cross. When arrows appear, press the arrow key that points in the SAME direction as the CENTRAL arrow. We will begin with a few practice runs.

Press space to begin.

Congruent Stimuli
Incongruent Stimuli
MOOD QUESTIONNAIRE

Each of the words below describes a feeling or mood. Please use the rating scale next to each word to describe your feelings at the moment.

Work quickly but be sure to mark one answer on each line, this should only take 1-2 minutes

EXAMPLE:
Relaxed
1 Circle 1 if you definitely do not feel relaxed at the moment
2 Circle 2 if you do not feel relaxed at the moment
3 Circle 3 if you are unsure if you feel relaxed at the moment
4 Circle 4 if you feel slightly relaxed at the moment
5 Circle 5 if you feel very relaxed at the moment

<table>
<thead>
<tr>
<th>Word</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
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<td>Restful</td>
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<tr>
<td>Sleepy</td>
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<tr>
<td>Anxious</td>
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<td>Energetic</td>
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<td>Nervous</td>
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<td>Calm</td>
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<td>Tired</td>
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<td>Alert</td>
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<tr>
<td>At-rest</td>
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<tr>
<td>Drowsy</td>
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<td>Fearful</td>
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<tr>
<td>Lively</td>
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<td>Laid-back</td>
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<tr>
<td>Exhausted</td>
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<tr>
<td>Worried</td>
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<tr>
<td>Quiet</td>
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<tr>
<td>Wide-awake</td>
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<tr>
<td>Tense</td>
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<tr>
<td>Fatigued</td>
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</table>

Please remember to turn over
Please indicate by marking the appropriate point on the line, your response to the following questions:

e.g.

How happy do you feel now?
Not at all
happy

Very happy

How hungry do you feel now?
Not at all
hungry

Very hungry

How full does your stomach feel now?
Not at all
full

Very full

How well do you feel you can concentrate now?
Not at all

Very well
APPENDIX D: Comparison of the Blood Glucose, Plasma Insulin and Blood Lactate Concentrations following the High and Low GI Breakfasts

The following figures compare the blood glucose, plasma insulin and blood lactate concentrations following the high and low GI breakfasts in chapter VII (data are mean ± S.E.M.).

D1: Blood Glucose Concentration

Resting Trials: Breakfast by session time interaction, p = 0.026

Exercise Trials: Breakfast by session time interaction, p = 0.002 (* HGI > LGI, p < 0.05)
D2: Plasma Insulin Concentration

Resting Trials: Breakfast by session time interaction, p = 0.024 (* HGI > LGI, p < 0.05)

Exercise Trials: Breakfast by session time interaction, p = 0.002 (* HGI > LGI, p < 0.05)
D3: Blood Lactate Concentration

Resting Trials: Breakfast by session time interaction, p < 0.001 (* LGI > HGI, p < 0.05)

Exercise Trials: Breakfast by session time interaction, p < 0.001 (* LGI > HGI, p < 0.05)