MEASURING CHILDREN'S WORKING MEMORY:

The influence of titrated time constraints on complex span tasks and the relationship with higher order cognitive abilities.

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Dedicated to

Philip James Leamy

&

To the memory of my grandparents

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TABLE OF CONTENTS

List of Tables

Chapter Six

Chapter Seven

List of Figures

Abstract

This thesis examined working memory (WM) and high-level cognition (HLC) in children. Previous research has shown that reducing maintenance opportunities in complex span tasks (CSTs) by restricting processing times can strengthen the WM-HLC relationship. This suggests that maintenance strategies are unimportant in the WM-HLC relationship. However, the restriction of processing times equally for all participants has not previously been addressed. This thesis assessed WM in 92 children aged seven to eight years of age using computer-paced numerical, verbal and visuospatial CSTs that titrated processing times individually for each child. Performance was compared to that in a condition where processing times were not restricted. Based on multi-component theories of WM, domain-specific and domain-general relationships with HLC (i.e. nonverbal reasoning, reading, mathematics) were examined. The effects of time constraints on the underlying mechanisms of each CST (storage, processing time, recall time, processing accuracy), their relationships with each other, and with HLC were investigated. In addition, the contributions of the broader executive abilities of inhibition and task-switching to the WM-HLC relationship were examined. Finally, the link between current WM abilities and mathematics performance two years later was also explored. Results showed that the two administration conditions accounted for shared and unique variance in HLC, suggesting measurement of different *and* similar cognitive abilities important in certain higher-order cognitive tasks. Examination of the underlying CST mechanisms showed that numerical WM best predicted concurrent HLC, with processing time replacing storage as a predictor when time constraints were introduced. Longitudinally, numerical, verbal and visuospatial WM predicted mathematics two years later. This identified WM capacity in seven to eight year olds important in mathematical ability at the ages of nine to ten years. Task-switching and inhibition did not predict HLC. Implications for multi-component and attention-based theories of WM, the importance of processing speeds and the role of maintenance strategy in the WM-HLC relationship are discussed.

Thesis Structure

This thesis consists of eight chapters. The first two chapters provide an overview of key working memory theories, and of previous research into the link with high-level cognition. A detailed description of the methodological approach is given in Chapter Three. Chapters Four to Seven cover the principal aims of the thesis: The relationship between working memory and high-level cognition in children, the effect of temporal constraints, and the importance of individual differences in processing speed. These chapters consist of a brief introduction of the research rationale, the relevant research questions, details of each investigation, results and a discussion. Finally, Chapter Eight provides a general discussion and conclusion.

1 Chapter One: General Introduction: Working Memory

This chapter provides an overview of the definition, structure and development of working memory.

1.1 Definition of key terms used in the chapter

Working memory (WM), generally defined as the ability to store and process information concurrently in order to achieve a known goal, is a concept which has become increasingly ubiquitous in the field of cognition since the influential model developed by Baddeley and Hitch (1974). However, WM as a construct has developed considerably since Baddeley and Hitch's conceptualization. Whilst the terms "short-term memory stores" and "working memory" are used interchangeably in the research literature, a review by Jarrold and Towse (2006) made a clear distinction between them, stating that short-term memory "refers to an individual's ability to store or maintain information over a limited time period, while WM refers to the ability to hold information in mind while manipulating, and integrating other information in the service of some cognitive goal" (p. 39). However, the term "executive-loaded working memory" (ELWM) is also used to describe the ability to manipulate and store information at the same time (Henry, 2012). This definition of ELWM is consistent with that of Jarrold and Towse (2006), in that it describes an ability to direct attention to processing an additional task, whilst still maintaining information in short-term memory (Henry, 2012). There are, in addition, those authors who refer to the concept of updating as the cognitive ability to store, monitor and modify information in an accessible state (Bull & Lee, 2014; Iuculano et al., 2011; Lee et al., 2011; Lehto & Juujärvi, 2003; Miyake et al., 2000; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011). St Clair-Thompson and Gathercole (2006) assessed children on four complex span tasks and two measures considered to assess the construct of updating. It was found that all of the tasks loaded together on the same factor, leading them to conclude that measures of WM and updating assess the same underlying construct.

In this thesis, ELWM and WM are considered as the same construct, with short-term memory being differentiated as required. Similarly, measures of updating and WM are considered as assessing that same construct, whether referred to as updating, ELWM or WM in any cited research. Any differentiation between the three concepts is provided as necessary.

Executive function, also referred to as the executive functions or executive functioning, has varied etymology. In the neuropsychological literature it is an umbrella term describing the cognitive processes that are required when automated or routine behaviour is insufficient to achieve a known goal or goals (Norman & Shallice, 1980/1986). In this context, it is considered to include WM along with other constructs such as planning, problem solving and decision-making (Pennington & Ozonoff, 1996). From this perspective, such processes are linked, but not limited to the frontal lobes of the brain (Damasio, 1996). Conversely, in cognitive psychology, executive function is commonly defined as those constructs governed by the central executive system of the multi-component model of WM (Baddeley, 1996; Baddeley & Hitch, 1974). In this model, the central executive is defined as a system that manipulates visuospatial and phonological information in conjunction with the use of short- and long-term memory stores to enable individuals to direct attention to relevant information, suppress irrelevant information, inhibit inappropriate behaviour and perform multiple tasks concurrently.

The definition of executive function as describing those functions governed by the central executive as a component of the WM model (Baddeley, 1996; Baddeley & Hitch, 1974) is used in this thesis. Any reference to research that considers executive function from a neuropsychological perspective is clarified as required.

1.2 The structure of working memory

The theoretical framework used for investigations into WM in this thesis was the multi-component model (Baddeley & Hitch, 1974). It is noted that there are challenges to this model (e.g. Cowan, 1999), based mainly on the premise that WM is a unitary, not a multi-component construct. In the interest of providing a broad understanding of WM, and to allow theoretically contextual discussion of the findings from the empirical chapters in this thesis, such theories are discussed in Section 1.4. However, to provide a framework for investigation into WM (and its relationship with HLC), a detailed discussion of the multi-component model of WM is provided here.

Evolving from the Atkinson and Shiffrin multi-store model of memory (1968), the model of WM developed by Baddeley and Hitch (1974), and subsequent revised versions (Baddeley, 1986; Baddeley, 2000), consist of three elements: an attentional control system referred to as the central executive; and two sub-systems responsible for the temporary storage of phonological and visuospatial material. These latter two systems are known as the phonological loop and the visuo-spatial sketchpad, respectively. A fourth limited capacity component, the episodic buffer, has been added to the original multi-component model of WM to account for the temporary storage of information from sensory and long-term memory for use in conjunction with visuospatial and verbal-auditory information (Baddeley, 2000; Baddeley, Hitch & Allen, 2009). However, the concept of the episodic buffer as part of the multi-component model has been questioned in subsequent research. This is discussed in greater detail in section 1.2.4.

1.2.1 The central executive

Although originally defined as the capacity to temporarily store information for the purpose of processing (Baddeley & Hitch, 1974), the central executive has since been redefined (Baddeley, 1996; 1993) and its function is now equated with the supervisory attentional system (SAS) developed by Norman & Shallice (1986). Its previous role as a temporary memory store has since been allocated to the episodic buffer (Baddeley, 2000) (see Section 1.2.4). The SAS is regarded as responsible for regulating and directing attention allowing the inhibition of automatic responses in order to control and promote behaviour consistent with known goals and objectives. Shallice (1982; 1988; Shallice & Burgess, 1991) has categorized these functions as necessary in certain situations such as decision making, error correction, dealing with novel situations, and inhibiting habitual, yet inappropriate, responses. With regard to the central executive defined by Baddeley (1996; 1993), its role in working memory is defined as directing attention to relevant information, suppressing irrelevant information, inhibiting reaction to irrelevant information, and switching attention between different processes (Baddeley, 2000; Baddeley, Chincotta, & Adlam, 2001).

This concept of an executive cognitive ability is supported by Posner and Petersen (1990) who proposed an "executive" component of the attentional system responsible for focusing on certain features of a surrounding environment. It has also been argued that such “executive function” is a control process for tasks required in all environmental and situational contexts (Denckla & Reader, 1993). In their review of neurophysiological, neurobiological, neuroimaging and computational studies, Miller and Cohen (2001) saw such control processes (e.g. maintenance of goal representations) as occurring in situations in which task-appropriate responses are promoted in the prefrontal cortex (PFC). They theorised that the PFC in turn exerts control over a range of thought processes such as selective attention, error monitoring, decision-making, memory, and response inhibition. These specific cognitive constructs have been further researched proposing the role of the PFC in executive abilities such as planning future action, retaining information in WM for future execution, and inhibiting unnecessary actions (Pennington & Ozonoff, 1996). In accordance with Norman and Shallice (1986), research has suggested that such processes are invoked when task novelty is high. For example, the appropriate task demands in a given situation are contrary to an automatic response or the situation has not previously been experienced (Hayes, Gifford, & Ruckstuhl, 1996). Therefore, executive cognitive ability is necessary to deal with a specific challenge, requiring the individual to plan a response rather than react to a stimulus or event in the environment (Borkowski & Burke, 1996; Scholnick & Friedman, 1993).

Research over the past twenty years has lent considerable support to the theory that cognitive control (i.e. executive function, SAS, WM) is an intrinsic requirement for optimal functioning in everyday life (Anderson, Jacobs & Anderson, 2008). Furthermore, research has shown that children exhibit developmental increases in executive function ability from infancy to adulthood (Anderson, 2002). Specific to the current research, a critical period of growth in the PFC between seven and eight years of age has been linked to developmental increases in executive functions (Anderson, 2002). For example, it has been found that seven-year-olds struggle with switching between tasks based on moderately complex rules but show greater ability from seven to nine years of age with maturation continuing through to early adulthood (Anderson, 2002).

However, the identification of such constructs is somewhat challenging. This issue was highlighted in the research of Miyake et al. (2000), who addressed what is known as the task impurity problem (Burgess, 1997; Stuss & Levine, 2002), in their seminal study investigating the unity and diversity of cognitive constructs considered to be executive functions. This impurity issue evolves from the very nature of executive functioning; that such functioning is identified via other cognitive events, so individual differences in cognition such as language, reading or counting will most likely influence performance on measures of the central executive that require processing of similar stimuli. Therefore, there is difficulty in distinguishing the interrelated processes evoked when undertaking a task designed to measure executive functioning, as overall task performance will also encapsulate other functions, thus polluting the findings from the task. In addition, Miyake et al. (2000) saw that the selection of tasks aimed at measuring executive function were incongruous in terms of their collective objective, as the same task has been used to measure very different constructs of executive function, whilst conversely the same construct has been measured by very different tasks. For example, they cite tasks such as the Wisconsin Card Sorting Test (Grant & Berg, 1948) and Tower of Hanoi (Krikorian, Bartok & Gay, 1994; Shallice 1982) being applied variously to the assessment of mental set shifting, inhibition, flexibility, and problem solving. Therefore, they sought to clarify some of the ambiguity in executive function assessment and test the ability to distinguish between the different constructs. Focusing on inhibition, switching and updating, they analysed multiple manifest variables to identify factors at the latent (i.e. underlying) level. Confirmatory factor analysis implied that, although correlated, these factors were indeed separable. Moreover, structural equation modeling showed differentiated contributions between the constructs to executive task performance.

A subsequent review by Miyake and Friedman (2012) summarised more than a decade of research on individual differences in executive functions. Most relevant to this thesis is the notion that, although executive functions are derived from a common, fundamental ability, it is also possible to identify a degree of separability between them. Miyake and Friedman quoted studies that have demonstrated a three-factor structure (i.e. updating, shifting and inhibition) in adult twins (Friedman, Miyake, Robinson, & Hewitt, 2011) and in eleven-year-olds (Rose, Feldman & Janowski, 2012). However, other studies have found a two-factor structure of WM and shifting, wherein inhibition was not identifiable in seven- to twenty-one-year-olds (Huizinga, Dolan & van der Molen, 2006) and nine- to twelve-year-olds (van der Sluis, de Jong & van der Leij, 2007). Conversely, other research found that WM and a combination of inhibition and shifting created a two-factor model in six- to eight-year-olds (van der Ven, Kroesbergen, Boom & Leseman, 2013) and five- to thirteen-year-olds (Lee, Bull & Ho, 2013). Interested in the fundamental cognitive and biological drivers of the diversity identified, Miyake and colleagues developed a research framework (i.e. termed “unity/diversity”) focused on examining the substructure of executive function. Initial research has demonstrated two important and clarifying findings that may explain the contradictory research of Huizinga et al. (2006), van der Sluis et al. (2007), van der Ven et al. (2013) and Lee et al. (2013).

Firstly, after accounting for a unified executive factor (i.e. a latent variable created from all nine tasks commonly used by Miyake and colleagues to measure updating, shifting and inhibition), inhibition did not demonstrate unique variance in adults (Friedman et al., 2008) or children (Friedman, et al., 2011). This suggested that a specific inhibition factor does not exist. Secondly, the unity/diversity model offers a division of the task-switching factor encompassing stability and flexibility. It is argued that actively maintaining a task goal (stability) interferes with the ability to flexibly switch to new tasks (flexibility) as required. Friedman et al. (2011) sought to demonstrate this in their longitudinal study of twins. The stability of the shifting factor was measured when the twins were two-years-old, and seventeen-years-old. It was found that group differences in self-restraint measures at two years of age remained constant at seventeen years of age when the better self-restraint ability group was significantly poorer on measures in the shifting factor. This was interpreted as an increased ability to sustain goal focus impeding cognitive flexibility. This dual structure, and the lack of findings regarding an inhibition factor, may go some way to explaining the varying findings discussed in this section.

Regardless of these recent findings, many influential studies into executive functions in children continue to focus on inhibition, switching and updating as the main factors involved in individual differences in executive functioning, with some success (Henry, Messer & Nash, 2012; Lee, et al., 2013; Passolunghi & Lanfranchi, 2012; van der Ven, Kroesbergen, Boom, & Leseman, 2012; 2013; Wolloughby, Blair, Wirth & Greenberg, 2012). Similarly, these constructs are intrinsic to the current study and are expanded upon here.

1.2.1.1 Inhibition

In the context of executive function, inhibition refers to the deliberate restraint of prepotent and/or automatic responses in order to attend to task-relevant stimuli (Baddeley, Emslie, Kolodny, & Duncan, 1998). Due to its influence in the acquisition of high-level cognitive abilities, inhibition has garnered substantial interest in the field of WM with varying findings. This construct is typically measured in children using a Go/No Go task where by a prepotent response is instilled during the first part of task participation; for example, there may be a requirement to press a button in response to a stimulus (e.g. a “go” signal). After several trials, a second “stop” signal is introduced after the first signal and the participant must inhibit responding for that trial. That is, they must inhibit the prepotent response in favour of the less frequently occurring one. The number of “go” signals prior to the “stop” signal varies between trials making the task less predictable. The number of errors on a Go/No Go tasks is inversely proportionate to a participant's inhibition ability (i.e. the higher the number of errors, the lower the person's inhibition rating).

Some theories of inhibition suggest that it is not a single construct but is, in fact, multiple processes representing a single ability (Hasher, Lustig & Zacks, 2007). The premise is that inhibition requires an initial, automatic response in order to recruit attentional focus for task purpose (i.e. access). However, this process may also allow irrelevant information into the attentional field. Therefore deletion is required to remove this irrelevant stimuli to allow for more streamlined processing of only relevant information. In addition, during processing, some information may become redundant as the task progresses, and this must also be deleted. Restraint is then required to prevent or limit responses that may be potent but are however, irrelevant to the task. This three-process view of inhibition is argued to be crucial to WM ability (Hasher & Zacks, 1988; Lustig, Hasher, & May, 2001). In support of this view, neurological research also suggests multiple processes are involved in inhibition; one responsible for the fast 'stop' mechanism (directed inhibition), and one responsible for slowing the 'go' signal in order to apply to most beneficial action (competitive inhibition) (Aron & Poldrack, 2006; Munakata et al., 2011; see Verbruggen & Logan, 2008 for a review).

With regard to the Go/No Go Task, directed inhibition could be viewed as responsible for the speed with which a participant can successfully inhibit response to a 'stop' signal, thereby avoiding an error. Competitive inhibition would relate to the participant's ability to momentarily delay responding to a signal to avoid a potential error (i.e. should the signal turn out to be a 'stop' rather than a 'go' signal). In relation to the view provided by Hasher et al. (2007), stop time and errors would measure restraint over a prepotent response in a stop trial. However, in order to measure the access process, it would be necessary to have a distractor present in order to measure a slow down in response times when there are irrelevant stimuli present (Hasher, personal communication, February 26, 2016). It may also be the case that deletion is required when the residual process of inhibiting action due to a ‘stop’ signal must be overcome (i.e. that representation must be deleted) before producing the relevant response for a ‘go’ signal (Hasher, personal communication, February 26, 2016; Rieger & Gauggel, 1999).

Although the multiple processes view of inhibition is acknowledged, the studies in this thesis intended to further explore the findings from previous research (e.g. Henry and Bettenay, 2010; Huizinga, et al., 2006). Therefore, the definition of inhibition is consistent with these studies and that by Baddeley et al. (1988), in that it enables the effortful inhibiting of an irrelevant response in favour of one that is beneficial to a task. For this purpose, measures of error and time were viewed as indicative of inhibition ability when the participant was required to impede a prepotent response in order to implement an appropriate one.

In terms of high-order cognitive abilities, Bull and Scerif (2001) investigated mathematical ability in seven-year-olds in relation to WM, inhibition and switching, demonstrating that poor mathematical ability was linked to low scores on inhibition tasks. They proposed that such a relationship corresponds to the SAS theoretical model (Norman & Shallice, 1986; Shallice, 1988; Shallice 1994; Shallice & Burgess, 1996) in that the lower ability children demonstrated difficulty in inhibiting an established strategy once it became apparent that the development of a new strategy was required. As the results also showed that these same children were able to develop an initial strategy and maintain it in memory, there was an argument for the dissociable nature of the components of executive function suggested in the SAS model. That is, strategy development is unimpaired, yet inhibition is impaired leading to an inability to switch to a new strategy. Further, a study by Henry et al. (2012) assessed children with and without specific language impairment (SLI) on ten executive function constructs. Whilst controlling for age, non-verbal IQ and verbal ability, results showed that the SLI group performed poorly on verbal and non-verbal measures of ELWM, verbal fluency and non-verbal planning and non-verbal inhibition. As these findings remained after verbal ability was accounted for, the study demonstrated that children with SLI show executive function deficits beyond those based on verbal ability.

Lee et al. (2013) conducted a longitudinal study, with children from the ages of five to fifteen, to identify the developmental trajectory of updating, WM, inhibition and switching. Using confirmatory factor analysis, they found that the factor structure began to change from the age of twelve years, later stabilising in fifteen year olds. The younger age groups demonstrated a two-factor structure consisting of updating and a combined inhibition/switching factor that vacillated between the unification of inhibition/switching, inhibition/updating and switching/updating from the age of six years to thirteen years. However, data for the fourteen to fifteen year old age groups demonstrated a robust three-factor model. Lee et al. argued that such findings implicate the importance of executive control in explaining diversity in executive functions.

Given the variation in findings with regard to inhibition as an executive function in children, the aforementioned unity/diversity model (Miyake and Friedman, 2012) proposes the wide-reaching nature of this factor and its strong correlation with general executive ability. Also, as previously discussed, there is considerable evidence linking executive functions with the development of the PFC (Miller & Cohen, 2001) and neurological changes from seven years of age have been shown to coincide with increases in executive ability (Anderson, 2002; Miller and Cohen, 2001). In consideration of these studies, should inhibition represent a common executive function, this would explain its fluctuating association with shifting and updating from the age of six years to thirteen years (Lee et al, 2013).

1.2.1.2 Task-switching

Task-switching describes the ability to alternate between cognitive processes in order to apply an appropriate action to a certain situation (Anderson, 1998). For example, when keeping track of a changing quantity (e.g. numerical amount), it may be necessary to switch between the two processes of addition and subtraction dependent on whether that quantity is increasing or decreasing. This ability, it is argued, requires resources from working memory to keep active the processes involved in more than one cognitive task (in the case of the current example, addition and subtraction) for the duration of task demand (Rogers & Monsell, 1995). Task-switching is typically measured using a task-switching paradigm (Jersild, 1927) where participants are required to perform a repetitive task (e.g. adding the quantity 3 to a number), and then to perform an alternating task (e.g. switching between adding and subtracting a quantity). As task-switching is considered to be effortful, requiring more cognitive resources (Logan, 2004), or more specifically executive control (Rubinstein, Meyer, & Evans, 2001), performance time and error rate in the non-repeating condition is expected to be higher than in the repeating condition. A measure of the difference in these performance indices across the two conditions is known as the switch cost (Monsell, 2003). Such tasks have also been used to identify the developmental trajectory of task-switching in children, and age related variance has been indicated (Cepeda, Kramer & Gonzalez de Sather, 2001; Crone, Bunge, van der Molen & Ridderinkhof, 2006).

Rule-based tasks are another method that has been used to measure task-switching in adults and children (Davidson, Amso, Anderson & Diamond, 2006; Diamond, Carlson & Beck, 2005). Such measures involve the repetitive application of a simple set of rules. Participants are then asked to use a different set of rules. As with switching-paradigm tasks, post-switch time and errors are recorded and compared to pre-switch performance to calculate the switch cost. An example of a dimensional switching task for children is the Dimensional Change Card Sort task (DCCS) (Zelazo, 2006), which consists of a set of cards containing pictures with two dimensions of category. For example, the picture may be of an animal or a vehicle, and can be blue or red (i.e. a blue car, a red rabbit, a red car, a blue rabbit). The participant may be asked to first sort the cards by colour (i.e. all the blue objects together, all the red objects together), and then sort them by object category (i.e. all the vehicles together, all the animals together). For older children, more complex switching rules can be introduced (e.g. if the card has a black border, sort by colour, if there is no border, sort by object).

Zelazo and Frye (1997), who introduced the DCCS task, argue against its definition as a task-switching paradigm. They posit that the rule structure involved in the task (i.e. if red then, if blue then) assesses an ability to manage multiple representations within a hierarchical structure. This view is known as the cognitive complexity control (CCC) theory (Zelazo & Frye, 1997). However, even the revised CCC theory (CCC-r; Zelazo et al., 2003), which was produced in response to criticisms that the rule structure of the task cannot explain performance when other elements are manipulated, has been challenged as overlooking the possibility of cognitive salience as an explanation for task failure (Towse, Redbond, Houston-Price & Cook, 2000). This view has been supported and extended by Diamond et al. (2005) who argue that the premise of the DCCS is akin to that in other similar tasks. Consistent with the description of task-switching in this thesis, Diamond et al. provided the following interpretation: “The DCCS, Wisconsin Card Sorting Test, and all task-switching paradigms require holding two pieces of information in mind plus inhibiting a dominant tendency” (p. 47). Noting this, and previous use of the DCCS to measure task-switching ability in children (Cragg & Nation, 2009; Garon, Bryson, & Smith, 2008), the DCCS is considered a measure of task-switching in this thesis.

Switching has been intensively researched with regard to its contribution to high-level cognition with varying results. Although Friedman et al. (2006) found task-switching to be unrelated to intelligence measures in young adults, it has been shown to play a role in mathematical ability by enabling strategy alternation in seven-year-olds (Bull & Scerif, 2001); and linked to non-verbal reasoning and reading ability in nine- to twelve-year-olds (van der Sluis et al., 2007). However, research has failed to identify a distinct task-switching factor in latent variable analysis with eleven- and twelve-year-olds (St Clair-Thompson & Gathercole, 2006), and more recent research has been unable to separate it from inhibition in seven and eight-year-olds (Van der Ven et al., 2012).

Given the variation in findings, it is again important to consider the aforementioned unity/diversity model (Miyake & Friedman, 2012) that proposes the dual structure of shifting ability (i.e. stability and flexibility) and argues that the maintenance of a task goal in WM may countermand the ability to switch strategy when required. This would go some way to explaining its complex role in mathematical ability (Bull & Scerif, 2001) and its elusive nature in latent variable analysis. Also, as previously discussed with regard to inhibition, a strong link between executive functions and the development of the PFC has been demonstrated (Miller & Cohen, 2001) and neurological changes from seven years of age have been noted (Anderson, 2002; Miller and Cohen, 2001). Variability of findings in the age groups discussed in this section may, therefore, be due to variations in these physiological and behavioural changes throughout childhood.

1.2.2 Verbal short-term memory

The system responsible for the storage of verbal information was originally named the phonological loop (Baddeley & Hitch, 1974), referring to the ongoing refreshment of acoustic information. Auditory material in this sub-system suffers from temporal decay after approximately two seconds, but voluntary recitation (i.e. rehearsal), either vocally or sub-vocally, refreshes this short-term memory trace making it available until decay reoccurs. Essentially, the information is kept in a “loop” until access to it is no longer required, or distraction renders rehearsal impossible and decay inevitable (Baddeley et al., 1975).

Verbal short-term memory is typically measured in children by verbally presenting a sequence of items to be recalled (e.g. digits, letters, words) in serial order, and has been shown to increase considerably in early childhood. For example, Isaacs and Vargha-Khadem (1989) found that seven-year-olds have a mean capacity of five digits, increasing up to seven digits in fifteen-year-olds. Explanations as to why this increase occurs include the acquisition of the aforementioned rehearsal activity. Consequently, rehearsal has been examined from a developmental perspective to better understand this increase in capacity throughout childhood and adolescence. McGilly and Siegler (1989) investigated the development of verbal rehearsal in five- and nine-year-olds by video-recording them whilst they maintained a list of digits in memory. They recorded any signs of rehearsal including covert articulation, moving of lips and repeated head-nodding. Children were then classified as using repeated rehearsal, single rehearsal (i.e. saying the list only once) or no rehearsal. It was found that the frequency of observed repeated rehearsal increased in children from five to nine years of age. Further research has shown that verbal rehearsal develops at approximately seven years of age (Gathercole & Hitch, 1993; Gathercole, Adams, & Hitch, 1994; Henry & Millar, 1991; 1993) and is viewed as a short-term memory aid that increases the core capacity. However, although not discussed here, it should be noted that there remains debate about when this ability emerges (Jarrold & Citröen, 2012) and whether rehearsal can fully explain increases in short-term memory capacity (e.g. Cowan & Vergauwe, 2015; Jarrold & Citröen, 2012).

1.2.3 Visuospatial short-term memory

The system responsible for the storage of visuospatial information was referred to as the visuo-spatial sketchpad in the Baddeley & Hitch model (1974), but is now commonly referred to as visuospatial short-term memory. Although thought to represent visual and spatial information collectively, Baddeley and Lieberman (1980) found that activity on visual tasks created minimal interference on spatial tasks, and vice versa. Similar findings are evident in other studies with children, which have found a steeper developmental trajectory for visual information than for spatial information (Hamilton, Coates & Heffernan, 2003; Logie & Pearson, 1997; Pickering, 2001). Also, findings in neuropsychological research suggest that these are two separate mechanisms within this sub-system (Klauer & Zhao, 2004; Smith & Jonides, 1997).

Visuospatial short-term memory is typically measured in children by visually presenting objects to be recalled either in terms of their location (i.e. visual or static information) or the sequence of their presentation (i.e. spatial or dynamic information). As with verbal short-term memory, the amount of information that can be stored in visuospatial short-term memory increases with age. For example, Hamilton et al. (2003) examined visual and spatial short-term memory capacity in four age groups ranging from six years to twenty-five years of age. Findings indicated a large developmental change between five years of age to twenty-five years of age for visual short-term memory, and a slower (yet significant) developmental change in this age range for spatial short-term memory.

Due to visuospatial short-term memory suffering rapid temporal decay similar to verbal short-term memory, it is assumed there is a form of maintenance, which facilitates information storage. Very little research addresses this possible phenomenon, though suggestions of refreshing are provided by some researchers (Henry, 2001; Logie, 1995; 2003; 2014; Ricker & Cowan, 2010). For example, Logie (1995; 2003) proposed that visuospatial short-term memory consists of two components separately responsible for storing visuospatial information (i.e. the visual cache) and for maintaining it to prevent decay (i.e. the inner scribe). The inner scribe would therefore be used similarly to the phonological loop, in that it reactivates the information in the visual cache, maintaining it for manipulation in WM. However, research with regard to maintenance of visuospatial information in short-term memory has received less attention in favour of the more manageable measurement of verbal short-term memory (Baddeley, 2007). Nevertheless, research has identified verbal recoding of visual stimuli as an effective maintenance strategy evident from as early as six years of age (e.g. Henry, 2008). A recent study by Henry et al. (2012) used rhyming pictures (e.g. cat, hat, bat) and non-rhyming pictures (e.g. frog, bus, cake) to identify the use of verbal recoding at various stages of development. The pictures were presented visually and recall was indicated by the participant pointing to the memoranda on a screen containing multiple objects. As presentation and recall were visually based, there was no requirement for the children to verbally recode the visual stimuli (i.e. name the object). Therefore, it was hypothesised that the naming of items would be a deliberate and strategic choice. If picture naming was employed, then rhyming pictures should produce a phonological similarity effect (Baddeley, 1966) not evident in non-rhyming stimuli. Three separate studies of four- to eight-year-olds found no evidence of verbal recoding in four-year-olds, with the emergence of this phenomenon from five years of age.

1.2.4 The episodic buffer

Temporary storage of information from sensory and long-term memory for use in conjunction with visuospatial and verbal-auditory information has been said to be the responsibility of the episodic buffer (Baddeley, 2000; Baddeley et al., 2009). Assessment of individual differences in episodic buffer capacity is sought by administering binding tasks wherein participants' ability to combine components of information into coherent units is measured. For example, a developmental study has investigated young children's ability to repeat meaningful sentences as separate from their ability to recall unrelated verbal items (Alloway, Gathercole, Willis, & Adams, 2004). It was found that children's scores on recall of meaningful sentences were significantly higher than their scores on recall of unrelated word strings. This led the researchers to conclude that a binding of items (e.g. words) of information into meaningful chunks (e.g. sentences) occurs to allow storage of increasing amounts.

Although the concept of the episodic buffer was introduced to represent the storage of multi-modal information (i.e. verbal and visuospatial), research into its binding ability has focused mainly on domain-specific information (see Nobre et al., 2013 for a review), one example being the aforementioned verbal binding study (i.e. Alloway et al., 2004). A more recent investigation into the role of the episodic buffer with regard to the maintenance of cross-domain information, found this capacity to be *separate* from that of the domain-specific verbal and visuospatial stores (Langerock, Vergauwe & Barrouillet, 2014). This suggests that, when there is a requirement to bind units of information from both the verbal and visuospatial domains, the episodic buffer plays an important role. However, when the information units are purely verbal or purely visuospatial domain, this binding function resides in the domain-specific stores.

However, with regard to measurement of the capacity of the episodic buffer, research is still in its early stages, with disagreement (or, limited understanding) regarding what distinct processes such measurement evaluates (Nobre et al., 2013). Indeed, the very existence of the episodic buffer as part of the multi-component model has been questioned. Studies using latent variable analysis to identify the individual components of the multi-component model tend to indicate a tripartite model comprised of the central executive and the two slave systems (e.g. Alloway, Gathercole, & Pickering, 2006; Kane et al., 2004), as opposed to a four-element system that includes the episodic buffer. This point is well demonstrated in a review by Cowan (2013), where it was argued that the existence of the episodic buffer could be the result of an “arbitrarily incomplete taxonomy of the systems in the brain” (Cowan, 2013, p. 6) caused by modular theories of WM. Furthermore, Cowan argues that the episodic buffer may be equal to activated long-term memory traces as defined by the embedded-process model (Cowan, 1999), which is discussed in Section 1.4.1.

Given the paucity of studies into the episodic buffer in children, it was felt that a solid research base upon which to build further findings was not available. Therefore, it was decided that this construct would not greatly benefit the current research aims, and study of it was therefore excluded from the empirical chapters in this thesis.

1.3 The development of working memory

In order to discuss how WM develops, it is necessary to first understand the determinants of its capacity, and how they are measured. The concept of WM as a limited capacity that develops throughout childhood is well founded (Barrouillet & Camos, 2001; Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; Gaillard, Barrouillet, Jarrold, & Camos, 2011; Gathercole, Pickering, Ambridge, & Wearing, 2004; Henry, 2012; Hitch, Towse, & Hutton, 2001; Lee et al., 2013; Towse, Hitch, & Horton, 2007). However, the reasons behind this development are, as yet, unconfirmed. Theories that explain such development include the concept of a pool of cognitive resources that must be shared between processing and storage (Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980, 1983; Just & Carpenter, 1992) to enable the maintenance of representations in WM for manipulation. From this perspective, working memory capacity is restricted by the limited nature of these resources.

An alternative theory argues that, when manipulating information in WM, it is necessary to switch from processing activities to the maintenance of storage items in order to prevent their temporal decay (Towse & Hitch, 1995; Towse et al., 1998; 2002). In this respect, working memory capacity is limited by the speed with which processing can be completed; the quicker items are processed, the sooner maintenance of memoranda can be resumed and the less likelihood there is of decay.

Investigation into the premise of both of these theories has led to the development of an alternative model; that is, the time-based resource-sharing (TBRS) model. The TBRS account of WM posits the existence of a rapid micro-switching ability that enables the refreshing of memory items during small gaps in processing (Barrouillet & Camos, 2004; Barrouillet & Camos, 2010; Camos & Barrouillet, 2011; Barrouillet, et al., 2009).

An effective way to demonstrate the strengths and limitations of each of these theories of capacity is to view them in terms of how they are measured from a developmental perspective. The following sub-sections examine the methods of assessment applied by each theory in order to determine the underlying mechanism (or mechanisms) that are offered as an explanation for the capacity increase in WM.

1.3.1 The resource-sharing hypothesis

A seminal study by Case et al. (1982) developed a counting span task with which to identify the underlying causes of developmental increases in children's WM capacity. After counting an array of dots on a series of cards, the requirement was to recall the total for each card in serial order. The number of cards presented (and to be later recalled) varied across trials, and the maximum number of totals recalled in serial order denoted the child's WM span. It was found that this span score increased from six to twelve years of age. In addition, it was found that faster counting speeds correlated with higher span scores. This was interpreted as evidence for a shared resource pool consisting of a processing space (i.e. for counting) and a storage space (i.e. for maintaining the count totals for later recall) as, when counting (or processing) speed is faster, fewer cognitive resources are required for that action, leaving more storage space available for memory items. When this task was adapted for adults (Case et al. 1982), its processing component was manipulated in terms of cognitive load by asking the adults to count in a previously unknown language. This resulted in the adult spans being reduced to a level comparable with six-year-olds. These results were interpreted as supportive of the resource-sharing hypothesis, in that age-related increases in span score were due to an increased processing efficiency. When demands on the processing component of the resource pool are lowered, the storage capacity is increased. Conversely, a more demanding cognitive task results in a decrease in available storage space.

1.3.2 The task-switching hypothesis

An alternative to the resource-sharing hypothesis was proposed by Towse and Hitch (1995; Towse et al., 1998; 2002) due to the former model's failure to address the effect of decay of memory items when the period of storage is prolonged. That is, when the cognitive load of processing is heightened, a parallel effect is an increase in the duration of the task, resulting in memory traces that would be at greater risk of temporal decay. Towse and Hitch argued that the correlation between counting speed and span score observed by Case et al. (1982) may be due to the fact that children who count faster can switch back to memory items sooner and, thus, refresh them and prevent decay. This would then result in an ability to recall more items.

Adapting the counting span task so that the duration of the available counting time was held constant, Towse and Hitch (1995) tested this hypothesis. The difficulty of the counting activity was then manipulated so that there was an easy (i.e. feature) condition, and a difficult (i.e. conjunction) condition. In the feature condition, blue squares were counted amongst an array of orange triangles. In the conjunction condition, blue squares were counted amongst an array of blue triangles. Pre-testing indicated an increase in counting time and counting error in the second condition that was taken to indicate greater difficulty.

Children aged from six to ten years were then tested on their ability in both conditions. The number of items to be counted in the fixed time period in each condition ranged from three to seven. A third condition (feature-slow) was then introduced, similar to the feature condition, but with an increased item range (i.e. from six to ten). This created a condition in which counting duration was the same as the conjunction condition, but with a lower cognitive load. In accordance with the resource-sharing hypothesis (Case et al., 1982), it was predicted that span scores would be higher in the feature condition where cognitive load is low. However, Towse and Hitch also predicted that performance in the conjunction and feature-slow condition would be equivalent. This, they argued would be due to the counting time being the same across both conditions, regardless of cognitive load. This hypothesis contradicts the resource-sharing condition that argues for an influence of cognitive load as opposed to storage time. The findings of the study supported the hypothesis that faster counting would equate to better recall. This was consistent across all ages and was interpreted as indicating a process of switching between counting, and storage of the totals after stimuli presentation. Therefore the greater the processing load (i.e. counting), and the longer the counting time, the longer the delays in switching to storage items, resulting in memory decay.

The task-switching hypothesis has been further tested with manipulation of the number of objects in an array on the first card compared to the last card to be presented in a trial (Towse et al., 1998). It was found that when the count on the last card was high, recall was negatively affected. However, a large count on the first card in a trial had no effect on recall. This finding, it was argued, further demonstrated that WM capacity is not affected by cognitive load, as a large count on the first card should have an equal effect compared to a large count on the final card if cognitive load influences capacity. However, this was not the case and WM capacity was affected by the time required to store memory items only, as a large array on the first card had no affect (i.e. when there were no items to maintain in memory).

1.3.3 The time-based resource-sharing model

Further investigation into the interplay between the two functions of processing and storage within WM has led to the development of the aforementioned TBRS model (Barrouillet et al., 2004; 2009). The TBRS model argues that a single, limited resource of attention is shared between processing and maintenance and that rapid switching (referred to as micro-switching) between these two constructs facilitates WM span. This differs from the Towse and Hitch (1995; Towse et al., 1998; 2002) hypothesis in that the TBRS model supports the notion of switching during, as opposed to after, processing.

In order to test the existence of this switching ability, Barrouillet et al (2004) conducted a study in which either the processing duration (i.e. time allowed to perform the task) or processing load (i.e. number of items within the task) were manipulated. For example, in a reading digit span task, participants were asked to read a series of digits displayed on a computer screen, which constituted the processing component of the task. Concurrently, participants were asked to hold in memory a list of letters displayed individually at intervals between each processing component. This represented the recall component of the task. In order to vary cognitive load, both the number of digits in a series shown in the inter-letter interval, and the time allowed to read them were manipulated in separate trials. An item-to-time ratio was employed to determine cognitive load. As such, an increase in the number of digits, with a constant processing time allowance, created a higher cognitive load for the participant and, similarly, a reduction in the processing time permitted to read a fixed number of digits also increased cognitive load. The findings of these studies showed that the number of memory items that could be recalled in the storage phase was a linear function of this ratio; that is, the less processing time permitted per processing item, the lower the recall score. This was interpreted as showing that a limited processing time per item restricts opportunities to switch to, and therefore refresh, memory items.

The model has been investigated from a developmental perspective (Barrouillet & Camos, 2001; Barrouillet et al., 2009; Camos & Barrouillet, 2011; Lépine, Barrouillet, &

Camos, 2005). Barrouillet and Camos (2001) examined the developmental accounts of the resource-sharing (Case et al., 1982) and task-switching (Towse & Hitch, 1995; Towse et al., 1998; 2002) hypotheses. In a study of primary school children, Barrouillet and Camos (2001, exp. 3) assessed WM capacity in five-, eight- and eleven-year-olds across three conditions. In the first condition the processing component of the tasks required mathematical problem-solving, which was chosen due to its high cognitive load. In the second condition, a lower cognitive load of counting was used. In the third condition, a simple recital of the sound “baba” was introduced instead of a processing task, in order to prevent verbal rehearsal of memory items, with no (or low) cognitive load. The duration of the processing component was held constant across trials. It was found that the counting and “baba” conditions did not result in different span scores in eight- and eleven-years olds. Barrouillet and Camos interpreted this as supporting the task-switching hypothesis (Towse et al., 1998) as counting and saying “baba” similarly blocked rehearsal and therefore led to memory decay. However, increasing the cognitive load (i.e. problem solving) induced poorer span scores in nine- and eleven-year-olds. This was interpreted as supporting the resource-sharing hypothesis as increased cognitive resource requirements lessened storage capacity. As the source (i.e. time or cognitive load) of impact on span score differed across age groups it was postulated that a combination of individual and developmental differences in WM reflected differences in some fundamental ability. Interpreting this general ability as a controlled attentional resource (i.e. micro-switching) identified in adults (Barrouillet et al., 2004), a subsequent study was conducted to establish the developmental trajectory of this ability.

Barrouillet et al. (2009) investigated the effects of manipulating processing time, pace (the rate at which processing items were presented) and cognitive load in five- to fourteen-year-olds. The intention was to identify the development of the attentional-switching resource to refresh memory items. As discussed previously, the TBRS model argues that a micro-switching ability allows for the transfer of attention to storage in order to maintain memoranda during processing. It was found that manipulations of time and pace, similar to those used in adults (Barrouillet et al., 2004) had little effect on children below the age of seven. Furthermore, increases in this ability (i.e. switching efficiency) were observed from seven years of age through to adolescence. As such, it was argued that this micro-switching ability is the cause of WM development in these age ranges. This has been further supported by similar research with five-, six- and seven-year-olds (Camos & Barrouillet, 2011).

Lépine et al. (2005) further investigated the effect of time constraints on WM tasks in 11-year-old children by comparing performance on self-paced complex span tasks (CSTs) with complex processing stimuli (e.g. single digit equations) to that on CSTs where the time allowed for the processing component was restricted and the processing stimuli was relatively simple (e.g. reading out a list of letters). The study's aim was to assess whether these two task types measured the same or different abilities, with the prediction that the simpler, restricted tasks would demonstrate stronger relationships HLC. Based on the premise that WM is strongly related to high-level cognition (HLC)[1], two hypotheses were tested by Lépine et al. The first hypothesis was that time-restricted tasks with simple stimuli require fewer cognitive resources because a) they reduce the opportunity for strategic maintenance of memoranda (e.g. by rehearsal or refreshing), and b) the processing items are less cognitively taxing than, for example, solving an arithmetic problem. Therefore, they measure a fundamental WM capacity untainted by cognitive processes evoked by active maintenance and calculation. Should this fundamental WM capacity be important in HLC then these tasks would hold a stronger relationship with higher-order cognitive abilities such as reading and arithmetic, compared to the self-paced tasks. The second hypothesis was that the complexity evoked by self-paced tasks (i.e. by the complex processing items and the use of maintenance strategies) identifies high-level executive abilities that are important in HLC. Should this be the case, the self-paced tasks would hold a stronger relationship with

[1] This relationship between WM and HLC has been studied extensively (e.g. Barrouillet, 1996; Daneman & Carpenter, 1980; Turner and Engle, 1989), and is discussed in detail in Chapter Two of this thesis.

HLC compared to the time-restricted tasks.

It was found that the time-restricted tasks were more predictive of HLC than the self-paced tasks. This led the authors to conclude that high cognitive load (i.e. caused by complex stimuli and the use of maintenance strategies) is not important in the WM-HLC relationship. However, the Lépine et al. (2005) study presents two problems. First, without separating out the two mechanisms by which cognitive load was reduced (i.e. either by reducing maintenance opportunity or by using simple stimuli) it is not possible to identify whether the removal of one, or the other, or both of these factors are what strengthens the relationship with HLC. Second, as time restrictions were applied generically (i.e. each stimulus was presented on the screen for 1000ms, followed by a 350ms delay for all participants), the possibility that participants with slower processing speeds were disadvantaged cannot be ignored. Similarly, it is possible that the previous studies that found storage scores to be a linear function of the item-to-time ratio in CSTs in adults (Barrouillet et al., 2004) and children (Barrouillet et al., 2009; Camos & Barrouillet, 2011) may be limited by the same presumption that processing speeds were consistent across the sample.

These issues remain unexplored and, therefore, the TBRS model does not fully explain the relationship between processing and storage in WM tasks. This processing-storage relationship, the effect of time constraints on CSTs, and the subsequent relationships with measures of HLC are examined in this thesis. The resource-sharing and task-switching hypotheses discussed in this section are also considered.

1.4 Alternative theories of working memory

The WM models discussed so far are comprised of distinct components that, although interlinked, are responsible for specific, separate processes. As such, they can be considered non-unitary. However, there is another school of thought that considers WM to be a unitary construct in that it is not separable from other cognitive domains. A highly influential alternative to the multi-component model is discussed below. Following this account, the key differences between unitary and multi-component accounts of WM are discussed.

1.4.1 Embedded-process model

The embedded-process model is a highly influential alternative to the multi-component model. It considers WM to be a collective of processes temporarily holding information in order that they are accessible for a given task or tasks (Cowan, 1999; Cowan, 2008). The model posits that information required for WM (i.e. to be temporarily held for execution of a known task) is retrieved form a single, central memory store. However, the amount of information that can be maintained in this state is limited. Research by Cowan (2001; Cowan, Morey, AuBuchon, Zwilling & Gilchrist, 2010) and others (Gilchrist, Cowan & Naveh-Benjamin, 2008; Oberauer & Kliegl, 2006; McElree, 2001) has indicated this amount to be approximately four representational units of information, and that as long as information can be united to form a meaningful 'chunk' (Cowan 2010) it can be considered as a single item and therefore not load WM beyond that amount. Cowan gives the following example; "…to remember to buy bread, milk, and pepper, one can form an image of bread floating in peppery milk" (Cowan, 2010, p. 2). This image would be considered a single chunk to be maintained in WM. The process of creating a chunk (cf. 1.2.4) out of these pieces of information is referred to in various literature as 'binding' (Baddeley, 2000; Cowan, 2013; Cowan, Donnell & Saults, 2013).

When items or 'chunks' of information are present in WM, they must remain activated to avoid temporal decay. Similar to the Baddeley and Hitch model (1974), Cowan argues that there is a central processing component that is responsible for allocating resources to such maintenance. Although the embedded-process model allows for some use of rehearsal strategies, it posits a process of memory search and resultant attentional focusing as the main maintenance mechanism. This process of attentional refreshing is consistent with that referred to in the TBRS model (Barrouillet et al., 2004). Therefore, a difference between Cowan's theory and the Baddeley and Hitch model is that the embedded-process model limits WM capacity by the amount (i.e. chunks) of information that can be maintained by focusing attention on that information, whereas the multi-component model defines capacity limits by the use of strategies (e.g. maintaining verbal information by sub-vocal rehearsal). Although often seen as opposing the Baddeley and Hitch model (1974), Baddeley himself has argued that this model may be used to explain the interplay between the central executive and the episodic buffer (Baddeley, 2010).

In terms of WM development, the embedded-process model suggests a growth in storage capacity alone (i.e. as opposed maintenance strategy) is responsible for the increase in WM with age. To assess this, a recent study of seven-year-olds, nine-year-olds, and eleven-year-olds and adults examined whether familiarity with memoranda would account for developmental differences in WM capacity (Cowan, Ricker, Clark, Hinrichs, & Glass, 2014). The premise was that the use of familiar stimuli (i.e. letters) would identify faster encoding (i.e. the use of maintenance strategies and the benefit of knowledge in participants who were older compared to those who were younger). This, in turn, would be evident in their higher span scores indicating that knowledge, encoding and strategy use can account for developmental increases in WM capacity. If familiar stimuli did have this effect on WM capacity in older children, then the maintenance of unfamiliar stimuli (i.e. unfamiliar characters) should not produce the same result, as the benefit for older children would not be present. However, it was found that those children with sufficient knowledge of the letters used did not significantly vary in performance when unfamiliar characters were presented. When the participants with limited letter knowledge were removed from the analysis, the developmental increases in span were similar between the familiar and unfamiliar tasks. Cowan et al. (2014) argued that this was consistent with the view that WM capacity increased with age independent of factors such as strategy use, encoding and knowledge.

1.4.2 An evaluation of WM theories

There are four key elements of WM that should be compared across models in order to understand their accounts of WM's purpose (namely, the concurrent processing and storage of information in pursuit of a known goal). These key elements are: the method by which information is maintained in WM; accounts of why WM capacity increases throughout childhood; explanations of effect of concurrent processing on storage; and whether or not verbal and visuospatial WM are separate domains.

With regard to maintenance of memoranda, embedded-process theory argues that focusing attention on information keeps it active in WM (Cowan, 1999). This differs from the multi-component model that proposes the importance of phonological of verbal information (Baddeley & Hitch, 1974) and verbal recoding (Henry, 2008) and subsequent rehearsal of visuospatial information.

Linked to this are theories of development, where the multi-component model argues that the maturation of sophisticated maintenance strategies is what drives developmental increases in WM capacity (Henry & Millar, 1991; 1993; Henry et al., 2012). However, unitary theory (e.g. the embedded process model) argues that it is an innate storage capacity that dictates developmental increases in WM capacity (Cowan et al., 2014). With regard to the effect of concurrent processing on storage, Section 1.3 has already provided explanations from the multi-component stance (i.e. resource-sharing, task-switching, TBRS). It is the last of these that is most closely related to the accounts provided by unitary theory, in that processing activity in WM diverts attentional focus away from storage items thereby preventing refreshment of those items (Camos & Barrouillet, 2011).

Considering the concept of domain-specificity of WM memoranda, multi-component models argue that items from different sensory domains (i.e. verbal and visuospatial) reside in separate slave systems and are maintained within these discrete mechanisms (Baddeley & Hitch, 1974). It is argued that processing activity in WM has a domain-general effect on performance by impeding maintenance of memoranda in these systems (Towse & Hitch, 1995). Therefore, it can affect performance in a way that appears domain-specific, for example due to blocking rehearsal, which can cause a decrease in storage capacity within a specific domain (Jarrold et al., 2011).

Conversely, the embedded-process theory posits that, although domain-specific networks may encode either visual or verbal information in WM tasks, this is specific to STM. This model argues that a domain-general network of attentional processes are involved in the maintenance and retrieval of information in WM (Li, Christ & Cowan, 2014), and that items from different domains are maintained under the same mechanism. Therefore, unitary theory argues for the existence of a WM capacity that serves as a storage system for domain-general information and also directs attention to item-specific stimuli during WM maintenance (Cowan, 1995; Kane et al., 2004; Saults and Cowan, 2007).

The aim of this thesis was to investigate the relationship between WM and HLC. Explanations of how information is maintained in WM, the relationship between processing on storage in WM, and issues of domain-specificity and/or generality are important in understanding this relationship and, therefore, are addressed in subsequent chapters.

1.5 Summary

In order to provide a foundation of understanding for the research studies in this thesis, this chapter primarily reviewed literature that supports a non-unitary, multi-componential model of WM (e.g. Baddeley & Hitch, 1974) and related explanations of the development of WM were considered in this context (Camos & Barrouillet, 2011). Alternative, unitary theory, and the underlying mechanisms responsible for WM were also discussed (Li et al., 2014), as were the relevant theories of developmental increases in its capacity (Cowan et al., 2014). As is evident in these discussions, there remains some debate with regard to what constitutes WM and how its capacity is determined. Theories include the use of maintenance strategies such as rehearsal (e.g. Henry & Millar, 1991), micro-switching (Barrouillet & Camos, 2001), the role of processing speed (Camos & Barrouillet, 2011), and of various attentional processes (Li et al., 2014). These will be addressed in this thesis. The following chapter examines the research literature proposing WM to be highly predictive of high-level cognition in adults and children.

2 Chapter Two: Working Memory and High-level Cognition

This chapter provides an overview of the aims, rationale and justification for the work undertaken. It examines existing literature looking at the relationship between working memory and high-level cognition. The importance of the application of this knowledge in primary school learning is discussed. The research questions for the thesis are then stated.

2.1 Definition of terms used in the chapter

This chapter discusses the relationship between working memory (WM) and higher-order cognitive abilities. For the purpose of clarifying the terms that are frequently used in the literature, it is noted that much research alludes to the concept of an innate level of intelligence, separable from learned abilities such as those resulting from education, which are often called fluid abilities or *gF* (Unsworth, Redick, Heitz, Broadway, & Engle, 2009). However various terminologies are used, ostensibly referring to the same construct. Broadly, the other terms used are: IQ (e.g. Landerl, Bevan & Butterworth, 2004), reasoning (e.g. Cowan & Powell, 2014), non-verbal reasoning (e.g. van der Sluis et al., 2007), abstract reasoning (e.g. Unsworth et al., 2009) and fluid intelligence (e.g. Bayliss, Jarrold, Gunn & Baddeley, 2003). Furthermore, measures of this construct overlap in their application. For example, Raven's Standard Progressive Matrices (Raven, Raven & Court, 1998) and Raven's Coloured Progressive Matrices (RCPM, Raven, 2008) have been used to measure abilities described variously as IQ, reasoning, non-verbal reasoning, abstract reasoning, and fluid intelligence. In this thesis, IQ, reasoning, non-verbal reasoning, abstract reasoning and fluid intelligence will be considered as representing the same underlying construct. Any differentiation between each will be provided as necessary. The term 'non-verbal reasoning' has been used to describe the construct measured by the RCPM for the studies included in this thesis.

Additionally, the broader concept of high-level cognition (HLC), or higher-order abilities, differs across the literature in terms of the cognitive skills they embrace. For example, as well as fluid abilities, many studies cited in this chapter assess ‘crystallised’ abilities such as language development (Alloway & Archibald, 2008; Henry & MacLean, 2003), reading ability (Friedman & Miyake, 2004; Gathercole, Alloway, Willis, & Adams, 2006; Towse et al., 2008b) and performing mathematical calculation (Alloway & Passolunghi, 2011; Berg, 2008; Bull & Scerif, 2001; Swanson & Beebe-Frankenberger, 2004; Towse et al., 2008a). In this thesis, the specific higher-order cognitive ability (or abilities) in question will be clarified and defined as the research literature is discussed. High-level cognition in this thesis is indicated by performance on measures of non-verbal reasoning, reading and mathematics. Further detail is provided in Chapter Three.

2.2 Working memory and high-level cognition

Individual differences in working memory have been proposed as the main predictor of HLC in adults (e.g. Unsworth et al., 2009), and crucial to the development of high-order cognitive abilities in children (e.g. Gathercole & Alloway, 2004). This section examines the existing literature looking at the relationship between WM and HLC in adults and children.

2.2.1 Research with adults

Research into the relationship between WM and HLC has grown considerably since Baddeley and Hitch’s (1974) description of the role of WM in successful task performance. Studies of WM and fluid intelligence in adults have indicated a complex relationship between the components commonly believed to be responsible for WM capacity (i.e. processing and storage) and general fluid abilities (Unsworth et al., 2009; Unsworth, Fukuda, Awh & Vogal, 2014). Unsworth et al., (2009) administered a sequence of WM tasks assessing the numerical, verbal and visuospatial domains, seeking to identify their power to predict higher-order numerical and verbal ability and abstract reasoning. By examining the processing and recall components of the tasks, both in terms of timing and accuracy, a complex matrix of contributions to HLC was identified. Processing time and storage were found to correlate negatively with each other, consistent with previous research (Bayliss et al, 2003; Bayliss, et al., 2005; Friedman & Miyake, 2004). However, in contradiction to traditional resource theories (Daneman & Carpenter, 1980; Miyake, Just & Carpenter, 1994), processing speed and processing accuracy were found to be separable constructs. Structural equation modeling indicated that processing speed and processing accuracy both partially mediated the relationship between WM storage capacity and IQ. Also, processing time and processing accuracy accounted for significant variance in IQ separate to that of storage. Finally, processing accuracy, processing speed and storage showed stronger correlations with IQ than they did with each other. This was particularly surprising given the supposed interplay between these components during CST performance. This, it was argued, demonstrated that multiple processes, some of which can be assessed by CSTs, drive HLC. However, residual variance (i.e. that not explained by processing and recall performance) in the analysis highlighted that there remained an elusive component (or components) that may contribute to the relationship between WM and HLC.

Therefore, Unsworth et al. (2014) investigated the relationship between WM and fluid intelligence based on the following rationale: Strong correlations have been found between attention and WM in children (Gathercole et al., 2008) and adults (Kane & Engle, 2002). Further, core capacity (i.e. WM storage capacity unaided by maintenance strategies) has also been shown to correlate strongly with CST performance (Cowan, Morey, Chen & Bunting, 2007). In addition, secondary memory has been suggested as accounting for unexplained variance in WM performance (Mogle, Lovett, Stawski & Sliwinski, 2008; Unsworth & Engle, 2007). Therefore, Unsworth et al. (2014) investigated whether measures of attention, core capacity and secondary memory could explain the relationship between WM and HLC. With the aim of identifying the aforementioned variance unaccounted for in HLC (Unsworth et al., 2009), Unsworth et al. (2014) included measures of attention, core capacity and secondary memory, along with measures of WM processing and storage, and fluid intelligence. It was found that attention, core capacity and secondary memory each accounted for unique variance in WM storage, WM processing and fluid intelligence. Furthermore, each factor mediated the relationship between WM and fluid intelligence. Thus, it was argued that the relationship between processing, storage and fluid intelligence could be further explained by individual differences in core capacity, attention and secondary memory.

Contrary to these findings, a series of studies examining correlations between short-term memory, speed of processing, updating, attentional control, performance on CSTs and measures of fluid intelligence in young adults found that short-term memory held the strongest correlation with a latent variable for general intelligence across three studies (range: r = .83 to .90) (see Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008). Processing speed, updating, and attentional control did not reliably correlate with WM across the analyses, and were not significantly related to general intelligence after controlling for short-term memory. This could indicate that executive abilities such as attention and the necessary skills in completing CSTs (i.e. speed and switching) do not play a role in explaining the relationship between WM and HLC.

Furthermore, theories of WM and attention have demonstrated an almost isomorphic relationship (Cowan, 1995; Engle & Kane, 2004; Kane et al., 2004). Engle and Kane addressed just this point in a review of WM, attention and cognitive control. By revisiting the work of Baddeley and Hitch (1974) they maintained that WM consists, in part, of short-term memory stores. Considering Cowan's embedded process model (Cowan, 1999; Cowan, 2004) they incorporated the activation of long-term memory traces in their exploratory models. In addition, the concept of executive attention, common to both these theories (i.e. Baddeley & Hitch, 1974; Cowan, 1999) as a requirement to maintain goal focus and manage interference, was included. They also acknowledged that maintenance strategies (e.g. rehearsal) aid activation and preservation of memory items. From the review of two decades of research into WM, they maintained that when studies refer to WM, and its relationship with HLC, the sole concept being investigated is executive attention. That is, the measure of focus is not how such information can be stored in WM, nor the ability to apply maintenance strategies, but the ability to focus attention to do so. They argued that executive attention is required to manage interference, maintain goals, and filter out competing stimuli, which in turn enables maintenance of information and actions.

So if WM and attention are in fact, the same concept, high correlations between WM and HLC itself would add further complexity to the field of research into WM and attention as predictors of HLC. Colom, Rebollo, Palacios, Juan-Espinosa and Kyllonen, (2004) argue for just this phenomenon. Defining WM as comprising attentional focus and the maintenance and manipulation of information, Colom et al. (2004) assessed the relative contributions of latent variables representing WM and general intelligence (crystallised intelligence, spatial ability, fluid intelligence, processing and psychometric speed). They found WM to be the latent factor best predicted by intelligence (r = .96 average across three studies). These findings suggest that WM and general intelligence are highly related in adults.

The research discussed in this chapter so far (see Table 2.1. for a summary) demonstrates varying explanations for the relationship between WM and HLC. Processing speed seems to influence WM storage capacity, and has been shown to be separable from processing accuracy, with both components acting as mediators between WM and IQ (Unsworth et al., 2009). Unexplained variance has shown the possible existence of other factors explaining the WM-HLC relationship, which have variously been identified as attention (Kane & Engle, 2002; Unsworth et al., 2014), core capacity (Cowan et al., 2007; Unsworth et al., 2014) and secondary memory (Mogle et al 2008; Unsworth et al 2014). Yet other research has cited the overriding influence of short-term memory (Colom et al., 2008). Furthermore, studies that have demonstrated an almost isomorphic relationship between attention and WM (Cowan, 1995; Engle & Kane, 2004) and WM and IQ (Colom et al, 2004) must also be considered. Whether WM is viewed as a single entity (i.e. executive attention), or consisting of multiple abilities (e.g. short-term memory, processing speed, processing accuracy, storage, executive attention), the implication is that measurement of its capacity is multifaceted. For example, should executive attention be important in WM performance then this factor must be assessed in order to identify its relationship with HLC. Similarly, if processing speed wields significant influence, then measurement of this ability, beyond storage, is central to understanding the link with HLC. Such issues are discussed later in this chapter. However, as HLC and WM ability in children is the focus of the studies in this thesis, the following section provides an overview of research in this field.

Table 2.1 Summary of findings regarding predictors of fluid intelligence in adults

Study	**Significant Predictors of HLC***
Colom et al. (2004)	Attentional focus
Colom et al. (2008)	STM capacity
Engle & Kane (2004)	Attentional focus
Kane & Engle (2002)	Attentional focus
Mogle et al. (2008)	Secondary memory capacity
Unsworth et al. (2009)	CST: faster processing time, greater processing accuracy, storage capacity
Unsworth et al. (2014)	Core capacity, attentional focus, secondary memory capacity

* Denotes positive relationships with increased HLC abilities

2.2.2 Research with children

Several studies have investigated the relationship between WM and HLC in children and have found links with academic ability (Alloway, 2009; Gathercole & Pickering, 2000; Henry & MacLean, 2002; Hitch, Towse & Hutton, 2001; Lépine, Barrouillet, & Camos, 2005), the development of language (Alloway & Archibald, 2008; Henry, Messer & Nash, 2012), expressive vocabulary (Henry & MacLean, 2003) and arithmetic (Bull and Scerif, 2001; Henry & MacLean, 2003; Passolunghi, Vercelloni & Schadee, 2007; van der Ven et al., 2012). In addition, longitudinal studies have found WM ability at the start of formal education to be predictive of subsequent academic achievement (Alloway & Alloway, 2010; Bull, Espy, & Wiebe, 2008).

Working memory deficits have also been linked to general learning difficulties (Gathercole & Pickering, 2000; Henry & MacLean, 2002; Henry & MacLean, 2003), mathematical learning difficulties (Andersson & Lyxell, 2007; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Iuculano, Moro, & Butterworth, 2011; Passolunghi & Siegel, 2004; Passolunghi & Cornoldi, 2008), and reading disabilities (Gathercole et al., 2006) in primary school children.

However, as with studies of WM and HLC in adults (Colom et al., 2008; Kane & Engle, 2002; Mogle et al 2008; Unsworth & Engle, 2005; Unsworth et al 2014), this relationship in children has also been shown to be multifaceted. For example, Engel de Abreu, Conway and Gathercole (2010) examined cognitive development in six- to nine-year-olds using multiple measures of short-term memory, WM and fluid intelligence (i.e. as measured by RCPM, Raven et al., 1986). Findings demonstrated that all three factors were highly related, yet separable, and that WM accounted for unique variance in fluid intelligence. Furthermore, WM and STM were shown to be distinct factors across the age range. That is, when controlling for shared variance between STM and WM, the residual variance (which Engel de Abreu et al. labeled as residual WM) demonstrated a significant link with fluid intelligence. This finding was interpreted as identifying a cognitive control mechanism, in line with Engle and Kane's (2004) argument that, rather than WM storage capacity being central to the relationship with HLC, it is the ability to control attention (i.e. cognitive control in the Engel et al. study) that defines the relationship.

The TBRS model of WM (Barrouillet et al., 2004) discussed in Chapter One supports this view. Examining the underlying mechanisms determining WM capacity, a linear, negative relationship between processing time and storage (i.e. slower processing speed equates to less storage) was observed in children from approximately seven years of age (Barrouillet et al., 2009; Camos & Barrouillet, 2011). However, rather than an indication of the importance of processing speed alone, it was argued that the correlations between faster processing speed and higher storage ability were due to faster processing allowing for more switching opportunities between processing items, resulting in attentional refreshing (Barrouillet et al., 2004; 2009). It is this attentional refreshing capacity that the TBRS model cites as being responsible for the high correlations between WM and HLC.

This supposition was supported in a study with children (Lépine et al., 2005; see Section 1.3.3), in which performance on two types of CSTs were compared. To briefly recap, in one condition, the processing component of the task was complex (e.g. reading span task) and in the second condition, the task was relatively simple (e.g. letter reading). The time available to perform the processing task in the second condition was restricted with the aim of minimising the opportunity to use maintenance strategies (e.g. attentional switching). The reason for reducing complexity in the second condition was to lessen the influence of individual differences in cognitive abilities analogous to the processing task (e.g. reading ability). It was found that performance in the 'easy' condition was more predictive of academic ability (i.e. literacy and mathematics) than the traditional tasks that were not temporally constrained. It was argued that the time-constrained, simpler processing task in the second condition restricted measurement to individual differences in a core attentional capacity. That is, influences of the use of maintenance strategies such as rehearsal, or individual differences in ability on the complex processing components common to traditional CSTs were removed, leaving only variability in attentional capacity which, in turn, enables micro-switching (Barrouillet et al., 2004; 2009; Barrouillet & Camos, 2007; Camos & Barrouillet, 2011).

Research has also examined the role of WM in predicting school performance in comparison to the predictive strength of IQ. From a longitudinal perspective, Alloway and Alloway (2010) examined the relative roles of WM (i.e. measured by two CSTs) and IQ (i.e. measured by two non-verbal subtests from the Wechsler Preschool and Primary Scale of Intelligence, Wechsler, 1990) in pre-school children and their academic attainment six years later. It was found that IQ and WM storage capacity both showed unique links to academic attainment with WM demonstrating greater predictive strength than IQ with regard to literacy and numeracy.

As with studies with adults (e.g. Unsworth et al., 2009), processing speed and storage capacity have been areas of focus in developing an understanding of the relationship between WM and IQ in children. Bayliss et al. (2003) investigated the mechanisms of WM that may dictate individual differences in capacity in eight- and nine-year-olds, and, in turn, how they might contribute to academic performance. Processing time and storage capacity were measured independently from combined WM measures. Individual differences in processing speed went some way to account for performance on the WM measures; however storage specific to the verbal and visuospatial domains was also related to WM ability. Furthermore, unexplained variance in WM scores (i.e. that not accounted for by processing and storage) significantly predicted academic attainment (i.e. reading and mathematics). The authors argued that this residual variance might represent the ability to coordinate the processing and storage of information in WM.

A subsequent developmental study of six- to ten-year olds found that age-related improvements in CST performance were driven by speed of processing and storage ability (Bayliss et al., 2005). Although this later study failed to replicate the previous findings in relation to domain specific storage (Bayliss et al., 2003), it supported the argument that processing speed and storage were both separately predictive of WM performance. In addition it was found that, in combination with WM, all three constructs contributed to HLC performance (reading, mathematics and IQ). These findings were consistent, to some degree, with a review by Fry and Hale (2000) that reported WM has a direct relationship with processing speed, acts as a mediating variable between speed and intelligence, and that processing speed and IQ consistently correlate throughout development.

However, other research offers contradictory findings. Berg (2008), in a study of eight- to twelve-year-olds, assessed ability in arithmetic calculation, reading, processing speed, short-term memory, and verbal and visuospatial WM. It was found that reading, short-term memory, and processing speed together did not eliminate WM as a contributor to arithmetic ability. Regression analyses showed that in the presence of short-term memory and processing speed, WM still accounted for unique variance in IQ. Furthermore, it was found that processing speed was important in arithmetic ability in younger children but not in older children. In addition, verbal and visuo-spatial WM each made unique contributions to arithmetic even in the presence of age, reading, processing speed, and short-term memory. This was interpreted as supportive of the findings in other research that contributions of processing speed are less evident as children become more proficient in mathematics (Salthouse & Kail, 1983).

Studies have also examined response durations in WM tasks (Cowan et al., 2003; Towse et al., 2008a; Towse et al, 2008b) to explain the relationship between WM and HLC in children. Cowan et al. (2003) used reading, listening, and counting CSTs, as well as standard digit span to assess WM and its link to academic skills in eight-year-olds. The study produced two main findings. Firstly, tasks that allow for the use of semantic cues in retrieval (i.e. reading and listening span) resulted in significantly longer recall durations. In addition, recall times accounted for a significant amount of unique variance in measures of academic attainment (i.e. beyond that accounted for by WM storage capacity). Towse et al. (2008a) conducted similar research, administering a reading CST, and assessing whether this task would predict reading and number skills in nine- and eleven-year-olds. It was found that the preparatory interval (i.e. the time duration prior to producing the first recall item, and inter-word pauses (i.e. the time duration between each item during recall) correlated with measures of literacy and numeracy ability. Further, Towse et al. (2008b) assessed seven- to nine-year-olds on an operation period task and an operation span task. The operations period task consisted of four visually presented maths problems, the answers of which were to be recalled following the completion of the fourth problem. The operation task also involved the completion of arithmetic problems but as with traditional span tasks, the number of items in a block increased incrementally as the child progressed with adequate recall. The duration of the preparatory interval, spoken words and inter-word pauses were recorded. It was found that duration at initial recall (i.e. first item) predicted ability and recall accuracy. As with the previous studies discussed here (Cowan et al., 2003; Towse et al., 2008a), slower recall times related to lower academic ability. The findings from these three studies indicate that analysis beyond WM storage scores and measures of processing speed can enhance an understanding of how WM abilities relate to HLC.

This section has discussed the predictive roles of WM storage and processing (including chronometric measures of processing and recall), and executive abilities (e.g. attention) with regard to HLC (see Table 2.2 for a summary). The following sub-section expands on the role of executive abilities, and reviews literature indicating the role of the central executive in higher-order cognitive abilities.

Table 2.2 Summary of findings regarding significant predictors of HLC in children

Study	Age in years	Significant predictors of HLC*
Alloway & Alloway (2010)	5 to 11	CST: Storage capacity
Bayliss et al. (2003)	8 to 9	Attentional focus
Bayliss et al. (2005)	6 to 10	Faster processing speed, STM capacity, CST: storage capacity
Berg (2008)	8 to 12	Faster processing speed, STM capacity
Engel de Abreu et al. (2010)	6 to 9	Attentional focus
Cowan et al. (2003)	7 to 9	CST: Shorter response durations
Lépine et al. (2005)	11	Attentional focus
Towse et al. (2008a)	8	CST: Faster recall times
Towse et al. (2008b)	9 to 11	CST: Faster recall times

* Denotes positive relationships with increased HLC abilities

2.3 The central executive and high-level cognition

The central executive is defined as the ability to direct attention to relevant information, suppress irrelevant information, inhibit reactions to irrelevant information, and switch attention between different processes (Baddeley, 2000; Baddeley, Chincotta, & Adlam, 2001). Effective performance on CSTs requires an individual to focus on stimuli for processing, switch attention from processing to storage, and select only the information from memory that is relevant to recall. Therefore, it is evident that optimal functioning of the central executive could be key to explaining CST performance and its relationship with HLC. Studies have examined the importance of the central executive in children's academic ability; specifically, its contributions to reasoning and reading (van der Sluis et al., 2007), language impairment (Henry et al., 2012) and mathematics ability (Bull & Scerif, 2001; van der Ven, 2012) have been considered.

Consistent with research into the structure of executive functions in children (Huizinga et al., 2006; van der Ven et al., 2012), these studies typically examined the roles of inhibition, shifting, and updating and their relative contributions to HLC, but findings are varied. For example, van der Sluis et al. (2007) sought to identify the influences of these three factors on reading, arithmetic and non-verbal reasoning in nine- to twelve-year-olds. Seven executive function tasks were used and performance on each was separated into executive and non-executive indices. To further explain, a non-executive measure would require rapid naming (e.g. of a letter) and an executive shifting task would require the naming of a letter or digit dependent on their location within a square. Therefore, performance on the simple processing component of the task could be separated from performance when there was an executive load. Using latent variable analysis, a shifting and an updating factor were identified, but a factor for inhibition was not evident. Only updating was found to be related to reading, arithmetic and non-verbal reasoning; and shifting was related to non-verbal reasoning and reading. Moreover, performance on non-executive components of the executive tasks (e.g. naming speed) was more strongly related to arithmetic and reading ability than the executive-loaded components (i.e. shifting or inhibition), indicating that executive ability may have a less influential role in HLC than tasks that require processing alone.

As discussed in Chapter One, deficits in inhibition, task-switching and WM have been shown to play a role in mathematical difficulties in six- to eight-year-olds (Bull & Scerif, 2001). Bull and Scerif found that difficulty in filtering out irrelevant information (inhibition) resulted in an inability to direct attention to new and more effective strategies (task-switching). However, other research has found no existence of a task-switching factor in eleven- and twelve-year-olds, but significant contributions of inhibition and updating for reading, mathematics and science ability (St Clair-Thompson & Gathercole, 2006). Further, studies using latent variable analysis to identify the structure of executive functions in children have been unable to separate shifting from inhibition in six- to eight-year-old children (e.g. van der Ven et al., 2013). This finding was also evident in research looking at the relative contributions of WM, inhibition and switching to mathematics ability in the same age group (e.g. van der Ven et al., 2012).

Van der Ven et al. (2013) went some way towards explaining the disparities in findings in relation to the factor structure of executive functioning in children by considering the influence of processing speed. They controlled for baseline speed in their measures of executive functioning, and included speed scores for inhibition and shifting. The findings demonstrated that variations in the structural organization of executive functions might be the result of differences in the methodologies used (i.e. controlling or not controlling for speed). This is in line with the findings of McAuley and White (2011), who found that processing speed accounted for significant variance in the developmental trajectory of WM and inhibition. Although the authors admitted to some degree of speculation, they suggested that, as well as allowing for better coordination of the processing and storage components of WM, processing speed may enable faster interpretation of environmental cues that can indicate the suitability of certain behaviours to achieve known goals. This interpretation is consistent with that of Fry and Hale (1996) who argued that processing speed underpins all constructs considered to be executive functions.

Another explanation for the discrepant findings from these studies could be related to the task-impurity problem, whereby pure measures of individual executive functioning constructs are very difficult to achieve, particularly across different age ranges. However, the use of latent variables should mitigate this problem, and more recent conceptualisations have shown that inhibition might be viewed as a general executive resource influencing other factors (Miyake & Friedman, 2012). This point is discussed in more detail in Chapter Six.

2.4 Working memory and high-level cognition in primary school learning

As discussed in Chapter One, extensive evidence exists to show that WM and other executive abilities develop significantly through early childhood to late adolescence and early adulthood (Anderson, 2002; Anderson, 1998; Huizinga et al., 2006; Lee et al., 2013). Section 2.3 discussed their role in general learning in a range of subjects such as English, mathematics and science (Alloway & Alloway, 2010; Henry & MacLean, 2003; St Clair-Thompson & Gathercole, 2006). Therefore, such research demonstrates the importance of WM ability in the formative school years.

Furthermore, evidence of the link between WM and HLC is supported by studies of the pre-frontal cortex (PFC). The PFC develops throughout childhood into early adulthood (see Best & Miller, 2010 for a review). Indeed, neuropsychological studies have demonstrated functional development throughout childhood, evident in executive abilities including attention, processing speed, task-switching and inhibition (see Anderson, 1998 for a review). For example, a neuro-behavioural study of WM development in four- to eight-year-old children, adolescents and adults (Luciana & Nelson, 1998) varied the complexity of a problem solving task in order to identify age-related differences in executive ability. In the least demanding condition performance was equivalent across the age groups. As task complexity increased, age-related differences emerged resulting in discrete ability levels at six years of age and seventeen years of age.

Research has also demonstrated how such findings translate into separate executive abilities around seven and eight years of age specifically. The development of attentional control has been shown to have a steep trajectory up to six years of age (e.g. Espy, Kaufmann, McDiarmid, & Glisky, 1999), when children begin to exercise faster impulse control with greater accuracy; and well-established ability is evident in nine-year-olds (Anderson, Anderson, Northam & Taylor, 2000). Similarly, information processing has been shown to develop rapidly from three to five years of age (Espy, 1997), with significant improvements observed in nine- and ten-year-olds (Kail, 1986). Furthermore, examination of the developmental trajectory of task-switching ability has revealed limitations in seven-year-olds, with steady improvements up to nine years of age (Anderson et al., 2000). With regard to inhibition, research by Brocki and Bohlin (2004) found evidence to suggest that this construct develops considerably from seven to nine years of age. However, it should be noted that, while some studies have found task-switching and inhibition to be non-separable in six- to seven-year-olds (van der Ven et al., 2013), others have found processing speed, inhibition and WM to be separate constructs from six- to twenty-four-year-olds (McAuley & White, 2011). Regardless, it is apparent that, when children are approximately seven- to eight-years-old, there is a period of transition from immature ability to more developed skills across attention, processing speed and task-switching and inhibition.

Such findings are further supported by research into mechanisms explaining capacity increases in WM, as discussed in Chapter One. According to the task-switching (Towse & Hitch, 1995) and resource sharing (Daneman & Carpenter, 1980) hypotheses, a developmental increase in processing speed can explain an enhanced ability to refresh decaying memory items (Towse & Hitch, 1995; Hitch et al., 2001), or free up storage space (Daneman & Carpenter, 1980). In addition, Bayliss et al. (2005) found that processing speed contributed, in part, to developmental improvements in CST performance due to decay prevention and faster reactivation of memory items. Furthermore, the TBRS model of WM argues for the development of an attentional switching capability to explain increases in WM capacity and it was found that this ability emerged at approximately seven years of age (Camos & Barrouillet, 2011). The emergence of these skills could be dependent on the aforementioned developmental increases in attention (Anderson et al., 2000; Espy et al., 1997) and task-switching (Anderson et al., 2000) identified in seven- and eight-year-olds. Also, the developmental trajectory of inhibition may be linked to accounts of WM development due to its role in interference resistance and preventing ineffective actions (Bull & Scerif, 2001; see Van der Molen, 2000 for a review).

The importance of these cognitive and neuropsychological developments and their link to HLC are important because typically developing children in primary education in the

UK are exposed to an intense learning process across the core subjects of mathematics, English and science at this time. Formal assessment of this learning process occurs at seven, eleven and fourteen years of age (Standards and Testing Agency, 2015) and affords the opportunity to identify those pupils who are falling below the expected standard. It is possible to identify individual differences in WM at an early age and there is strong evidence to suggest an understanding of the underlying mechanisms of its relationship with HLC and how it enables learning can contribute to cognitive deficit identification and subsequent intervention programmes. For example, in a study of seven-year-olds with low curricular achievement scores, Gathercole and Pickering (2000) found that low performers demonstrated central executive and visuospatial deficits. By looking at a single score from a small WM test battery, it was possible to identify the majority of students who were falling below expected levels of achievement. This study was important as it demonstrated the possibility of early detection of delays in education attainment in later years. Although this study was not longitudinal, it showed the potential for using WM ability to identify later performance in a range of key curriculum subjects.

With regard to longitudinal studies into the predictors of later academic ability in primary school, most recently, prospective mathematics ability has received increased attention. An example of this is the aforementioned neuroimaging research by Dumontheil and Klingberg (2012), which measured activity in the intraparietal sulcus (i.e. the area of the parietal lobe responsible for numerical representation) whilst six-to-sixteen-year-old participants performed visuospatial WM tasks. It was found that abnormal activity in this area of the brain during such tasks reliably predicted poor arithmetic ability two years later. This was evident even when controlling for behavioural measures of non-verbal reasoning and verbal WM. Aside from demonstrating the value of using neuroimaging technology to improve behavioural assessment, this study demonstrated a strong link between visuospatial WM and later mathematical ability. Such research adds weight to the use of measures of WM to identify later academic ability.

This thesis provides continued examination of WM, its underlying mechanisms and how they relate to HLC. This is based on the perspective that such investigation is important in explaining WM abilities and deficits in children and how they relate to HLC currently and longitudinally. Given the prevalence of processing speed as an influencing factor in the literature, specific consideration of this ability is included in the research methods used. This is discussed in Section 2.6.1, and in more detail in Chapter Three.

2.5 Measuring WM using time-restricted tasks

So far this chapter has focused on the relationship between WM and HLC. However, as can be seen from the studies cited previously, the method by which this relationship is measured varies, and evidence suggests that this too can affect the WM-HLC relationship. In Chapter One (see Sections 1.3.3 and 1.4.2), and the current chapter (see Section 2.2.2) reference has been made to the affect of time restrictions of CSTs and how this may, or may not, alter the relationship with HLC. This point is expanded upon here.

A review of existing studies that have used time-restricted CSTs has highlighted much variability on how these temporal constraints are applied. A summary of these studies is shown in Table 2.3. Primarily, two methods of placing time-constraints on CSTs have been used; one in which the experimenter controls the presentation of processing stimuli; compared to the use of computer-paced tasks are used to present stimuli for a pre-determined duration. In order to identify performance differences due to time restrictions, such tasks have been compared to CSTs where there are, supposedly, no time restrictions. For example, in studies with adults, Friedman and Miyake (2004) and St Clair-Thompson (2007), both used participant-led untimed tasks where the participant was in control of the pace of the task, initiating the display of processing stimuli. Performance was then compared to that on a ‘timed’ task in which the experimenter controlled the presentation of processing stimuli. However, in both these administration conditions, presentation of processing stimuli was delayed until the participant had completed the previous processing task and was therefore ‘ready’ to proceed to the next stage. Due to individual differences in processing duration, pace of presentation was not consistent across the sample. However, this method did mean that, in the timed condition, the participant could *not* delay moving to the next stage in order to implement maintenance strategies such as rehearsal.

However, Bailey (2012) and Lucidi et al. (2014) administered timed tasks using a computer-paced administration condition to determine when processing stimuli would be presented to participants. In this condition, the length of time it took a participant to complete the previous processing task did not affect the pace of presentation. Therefore, it was not possible for the participant to delay processing in order to implement maintenance strategies. In these two studies, performance was compared to a condition in which the experimenter triggered the presentation of subsequent stimuli once a response had been elicited from the participant (i.e. akin to the timed condition in the Friedman and Miyake, 2004 and St Clair-Thompson, 2007 studies).

In a similar study with children, Lépine et al. (2005) compared performance on a computer-paced CST to that on a participant-led task, and found the computer-paced task to be more predictive of HLC than the self-paced task. However, as mentioned earlier in this chapter, a further manipulation was included in the two administration conditions. In the participant-led task, the processing stimuli were rated as ‘complex’, in that the participant was required to either verify the veracity of a sentence (for reading span), or complete a single-digit, three-operand sum (for operation span). In the computer-paced task, ‘simple’ stimuli were used (i.e. reading out a series of letters; adding or subtracting ‘1’ from a base number).

Table 2.3. Summary of methodological approaches to placing time restrictions on CSTs in existing research

Study	Participant age	Time-restriction method *(Duration of processing task display)*	Comparison task
Bailey (2012)	Adults	Computer-paced (4 seconds)	Experimenter-led
Friedman & Miyake (2004)	Adults	Experimenter-led	Participant-led
Lépine et al. (2005)	11-year-olds	Computer-paced (1,500 milliseconds)	Participant-led
Lucidi et al. (2014)	Adults	Computer-paced (600 or 1200 milliseconds)	Experimenter-led
St Clair-Thompson (2007)	Adults	Experimenter-led	Participant-led

These administrative differences are important, as time restrictions in CSTs have been reported to increase their predictive strength with regard to HLC in some studies (Friedman & Miyake, 2004; Lépine et al., 2005; St Clair-Thompson, 2007), whereas other have reported that their relationship with HLC is comparable to that of unrestricted CST tasks (Bailey, 2012; Lucidi et al., 2014). Furthermore, none of these studies accounted for individual differences in processing speeds when defining the pace of presentation of the stimuli. Therefore, whilst findings of increased predictive power in time-restricted tasks has been interpreted as indicating a core capacity due to the curtailing of maintenance strategy use (Friedman & Miyake, 2004; St Claire-Thompson, 2007) or reduction in contamination from more complex cognitive abilities (Lépine et al., 2005), it is entirely possible that individual differences in processing speeds affected task performance and, subsequently, the relationship with HLC.

2.6 Working memory domains and relationships with HLC

Research has examined relationships between the domain-specific WM and certain higher-order cognitive abilities with varying findings. Investigation into reading abilities has consistently found strong links with verbal WM (e.g. Cain, Oakhill & Bryant, 2004; Daneman & Carpenter, 1980; 1983; Oakhill, Yuill & Garnham, 2011) and deficits in this area have been related to reading impairment (De Jong, 1998; Gathercole et al., 2006; Henry & Winfield, 2010; Swanson, 1994). Links between verbal WM and arithmetic are also well founded (Adams & Hitch, 1997; Bull & Scerif, 2001; Gathercole, Alloway, Willis & Adams, 2006; Jarvis & Gathercole, 2003; Towse & Houston-Price, 2001), but research has also shown that verbal ability in the first year of primary school does not predict maths learning in later years (Passolunghi, Vercelloni & Schadee, 2007).

Numerical and verbal WM have been shown to be highly related (Hitch, Towse & Hutton, 2001), but there is also supporting evidence for their separation (Baddeley et al., 1985; Leather & Henry, 1994), and research into the predictive strength of these two domains with regard to HLC has produced varying results. For example, numerical and verbal WM have been found to be better predictors of reading comprehension than visuospatial WM in six- to eleven-year-olds (Oakhill et al., 2011) and impairment in both these domains has been linked to poor mathematical problem solving (Passolunghi & Siegel, 2001). Yet Siegel and Ryan (1989) found that children with severe mathematical learning difficulties performed at typical levels on non-numerical WM tasks, but not on WM tasks that required counting and number storage. Similarly, a study by Hitch and McAuley (1991) found that children who had mathematical learning difficulties without reading difficulties underperformed on a counting span task but not a word span task (see also Peng & Fuchs, 2014 for a meta-analysis with supporting findings).

More recent research has found strong links between the visuospatial domain and mathematical ability. Assessing the central executive, verbal and visuospatial WM, processing speed, reading and mathematics ability, and academic attainment in six-year-olds and ten-year-olds, Li and Geary (2013) found that visuospatial WM had a steeper developmental trajectory than the central executive and verbal WM, and that mathematics ability in ten-year-olds was predicted by the development of visuospatial and numerical speed of processing from six to nine years of age. This supported research by Dumontheil and Klingberg, (2012) who, in a neurological study, found that visuospatial WM in six- to sixteen-year-olds predicted mathematical ability two years later.

With regard to relationships with different aspects of HLC in children, these findings suggest a degree of separability and similarity between the verbal and numerical domains; and further separability from the visuospatial domain. In addition, there is evidence of a varying developmental trajectory whereby separate WM stores contribute to HLC differently dependent on age. Furthermore, WM has been shown to be differently affected by time restriction in CSTs dependent on domain. For example, previous research with adults has found that the relationship between HLC and verbal WM was stronger when a verbal CST was time-restricted compared to when it was not. However, when the same manipulation was applied to a visuospatial task, the relationship with HLC was not significantly affected (St Clair-Thompson, 2007). St Clair-Thompson interpreted this as identifying limited strategy options for the visuospatial tasks, which were minimally affected by time limitations. This finding may be more pronounced in children given that verbal recoding of visual stimuli only begins to develop from five to six years of age (Henry, 2008: Henry et al., 2012), or possibly as late as seven years of age (Hitch, Halliday, Schaafstal & Schraagen, 1988). Therefore, children's performance on CSTs may be differently affected by time-restrictions depending on whether the processing stimuli are verbal or visuospatial.

2.7 Summary

To this point, Chapter Two has provided a review of research investigating the relationships between WM and HLC in children and adults; specifically it has highlighted the importance of WM during primary school, due to both brain development and the UK's education system's expectations for learning. Measurement of WM using CSTs has been discussed, along with studies that have examined different mechanisms within WM (e.g. executive attention, processing efficiency, and recall durations) and their relationships with HLC. In relation to this, the effect of time restrictions on CSTs has been examined, with findings suggesting that limitations affect the predictive strength of such tasks with regard to HLC. Finally, a brief review of research into how verbal, numerical, and visuospatial WM relate to HLC indicated certain CSTs might predict discrete higher-order cognitive abilities relative to the domain-specific STM stores they employ. Furthermore, measuring WM using CSTs has shown that there may be domain-specific differences in how numerical, verbal, and visuospatial tasks are affected by temporal constraints on processing; and that this could be due to variability in the use of maintenance strategies within the tasks.

The multi-component model (Baddeley & Hitch, 1974) has provided four decades of extensive contributions explaining the development of WM and its relationship to HLC. Given this longevity and productivity, this WM model has been used as the foundation for the current investigation into the relationship between WM and HLC. However, contributions from alternative theories are acknowledged and, indeed, have contributed to the design of studies in this thesis. Specifically, the assumption of the TBRS model (Barrouillet et al, 2004) that temporal factors within WM comprise its capacity limitations, and therefore explain its relationship with HLC, underpinned investigation into the relationship between CSTs and WM.

2.8 Thesis structure and rationale

Using a novel, computer-paced measure of WM, the objective of the current research was to assess WM capacity in primary school children and examine its relationship with HLC (i.e.

non-verbal reasoning, reading and mathematics). The childhood age of approximately seven and eight years is noted as a time of transition from passive to active maintenance in WM (see Section 2.2.2); when executive abilities play an important role in HLC (see Section 2.3); and a time of considerable cognitive development and intensive learning (see Section 2.4). Therefore, this age group was identified for two reasons. First, it is likely that considerable variability would be observed at this developmental stage providing a rich array of data with regard to individual differences; and second, identification of key cognitive factors that can predict academic ability would be valuable in the education setting at this early stage. The UK education system dictates that children undertake mandatory assessment of learning progression at seven, eleven and fourteen years of age. Such assessment enables the identification of children who are not progressing at the expected standards. Therefore, any deficits that relate to learning at this stage can contribute to the development of intervention programs to boost student performance toward expected levels.

Throughout the four empirical chapters in this thesis, HLC was assessed using measures of mathematics, reading and non-verbal reasoning. To ensure academic assessment was consistent with national standards, children were measured on their reading and mathematics abilities in relation to the teaching curriculum covered in Year 3. The tasks used and the related rationale is discussed in more detail in Chapter Three.

Measurement of WM employed computer-paced CSTs whereby time was restricted to allow for processing but no additional time for maintenance strategy use. Whilst previous studies have applied generic time constraints to CSTs, the novelty of this measure was that individual differences in processing speed were calculated at an individual level, *a priori* and used to place a time restriction on the processing component of the task for each child. Performance was compared to a condition in which the processing component had no temporal constraints, so the participant had control over the time allowed for processing the stimuli and, therefore, could choose to implement maintenance strategies to aid storage and subsequent recall.

The first study in this thesis investigated whether performance on CSTs predicted the higher-order cognitive abilities of non-verbal-reasoning, reading and mathematics. As discussed in Section 2.6, there is evidence to suggest that WM holds domain-specific relationships with HLC. Therefore measures of numerical, verbal and visuospatial WM were used to further understand these relationships. The predictions regarding domain-specific relationships are discussed in greater detail in Section 2.8.1. In addition, this study examined whether placing time restrictions on the processing component of the tasks altered the relationship with HLC compared to when no time restrictions were administered. The time-restricted tasks are referred to as computer-paced, and the WM tasks with no time-restrictions are referred to as experimenter-led (Research Question 1).

Then, the underlying reason for any difference in predictive strength between the various CSTs was investigated by looking in more detail at the component measures within each task. By examining individual storage, processing times, recall times, and processing accuracy in each condition, and assessing the individual contributions to HLC, any differences in how the tasks related to HLC were identified (Research Question 2).

Next, contributions to HLC from other key executive skills were considered. Namely, potential contributions of task-switching and inhibition to performance on measures of HLC were assessed to identify whether these constructs would account for variance in HLC over and above the contributions of the CST measures in all domains and conditions (Research Question 3). Finally, the longitudinal relationships between current measures of WM and future mathematical ability were examined in a sub-sample of children assessed (Research Question 4). The research questions that were investigated in this thesis are now explained in more detail, along with relevant predictions.

2.8.1 Research question one

What are the relationships between WM (i.e. numerical, verbal and visuospatial) and HLC (i.e. non-verbal reasoning, reading and mathematics) for computer-paced versus experimenter-led tasks in seven- to eight- year-old children?

Although there is evidence that performance on CSTs relates to performance on measures of HLC, the current thesis investigated whether introducing individually titrated temporal constraints on these tasks affected these relationships in important ways. More specifically, do time-restricted and unrestricted CSTs measure the same or different WM abilities, and do these abilities relate differently to HLC? The traditional interpretation of the relationship between WM and HLC is that WM tasks (e.g. CSTs) measure a cognitive ability to coordinate the processing and storage of information concurrently and that, as such a function is required in complex activities such as reading and mathematics, this ability relates to HLC (Baddeley, 1990). However, there is an alternative view that CSTs measure how much information can be temporarily retained in memory when a concurrent processing task switches attention away from its maintenance. It is argued that this fundamental attentional capacity relates to HLC (Barrouillet et al., 2004). Due to the elementary nature of this capacity, such a view argues that strategy use (e.g. rehearsal) can produce a biased measure of WM and disrupt the relationship with HLC (Lépine et al., 2005).

To test these two views of the WM-HLC relationship, the current study measured WM using individually titrated CSTs, and compared performance to that on CSTs where participants controlled their own processing times. The subsequent relationships with higher-order cognitive abilities were then examined for each administration condition. If CSTs measure a supervisory and coordinating ability in WM, then the experimenter-led task should predict HLC, as participants who use strategies to improve WM performance would produce higher span scores, and those participants would perform better on measures of HLC. However, if CSTs measure a fundamental attentional capacity then the computer-paced tasks, which reduce strategy opportunity, should be better predictors of HLC. In this latter prediction, higher span scores would represent individuals with a greater attentional capacity, and those participants would demonstrate higher HLC scores.

Consistent with research outlined in Section 2.8.1, it was also expected that a measure of visuospatial WM would relate to mathematics; verbal WM would related to reading and mathematics; and numerical WM would related to mathematics, and possibly reading, ability. Given that fluid intelligence in this thesis was measured using a non-verbal reasoning task, it was expected that visuospatial WM would related to this ability more strongly than measures of verbal or numerical WM. Finally, as research has shown that domain-specific CSTs have been differently affected by restrictions on processing times (St Clair-Thompson, 2007), it is possible that the relationship between visuospatial WM and HLC would be less affected by administration condition than the other two tasks. As use of maintenance strategies for visuospatial stimuli is only beginning to emerge in seven- to eight-year-olds (Henry, 2008), it was expected that the time restrictions on the CST would be minimally disruptive.

2.8.2 Research question two

Do the separate mechanisms employed in CSTs (i.e. storage, processing time, recall time and processing accuracy) relate to each other, and to HLC, differently when the time allowed for the processing component of the task is restricted compared to when it is not?

In exploring the effect of administration condition on the WM-HLC relationship, there was a need to look beyond the traditional measure of storage in CSTs to the underlying mechanisms of processing efficiency and recall duration. The first objective was to understand how certain CST mechanisms related to each other, and whether that relationship was affected by individually titrated time-constraints. Specifically the relationship between processing and storage was examined. According to the traditional view of WM, maintenance strategies aid recall, and this would be evident in longer processing times relating to higher span scores (Baddeley, 1986). Also, the view of WM as a limited attentional resource argues longer processing times relate to higher span scores, as each item being held in WM requires attentional refreshing at a rate of approximately fifty milliseconds per item in adults (Vergauwe et al., 2014). However, studies that have placed time restrictions on CSTs have found varying effects on storage capacity (see Section 1.3.3), and such variability may be due to the use of generic time constraints (see Section 2.5). Therefore, this study further investigated the change in the processing-storage relationship when individually titrated CSTs were administered, compared to when there were no time restrictions.

It was predicted that longer processing times in the experimenter-led condition would be related to higher span scores, consistent with the multi-component (Baddeley & Hitch, 1974) and the TBRS (Barrouillet et al., 2004) models of WM. Conversely, it was expected that shorter processing times in the computer-paced condition would be related to higher span scores indicating either task-switching (Towse & Hitch, 1995; Towse et al., 2002) to prevent decay of memory traces, or attentional switching ability in participants with faster processing speeds (Barrouillet & Camos, 2001; Camos & Barrouillet, 2011).

Processing accuracy was examined in or to understand whether processing time and accuracy represent a single processing capability (i.e. processing efficiency) or two separate abilities. It was speculated that processing accuracy would be differently affected by time-constraints compared to processing time, and that the two mechanisms would relate to each other differently in the two administration conditions. This would indicate that processing time and accuracy are separate constructs, and not a single resource as specified by the resource-sharing model (see Section 1.3.1)

The second objective was to look at the domain-specific (e.g. storage) and domain-general (e.g. processing) aspects of WM (see Section 1.4.2) and their relationships with HLC (see Section 2.2.2) to understand whether they were differently affected by time restrictions. The premise was that time restrictions on CSTs relate to the domain-general processing component (Bayliss et al., 2003; 2005) and possibly limit the domain-general construct of active maintenance (Lépine et al., 2005). It was predicted that when time-constraints were placed on the CSTs the role of domain-general processing in order to maintain information in WM would be more evident, and that children who could process stimuli faster would also score higher on measures of HLC. Therefore the prediction for the current study was that processing times in the computer-paced condition would predict HLC, and that this would not be specific to a WM domain or domains.

Consistent with existing research (e.g. Cowan et al., 2003; Towse et al., 2008a;

Towse et al., 2008b), it was also predicted that recall time would indicate domain-specific abilities and therefore relate to HLC along with storage in the untimed condition. More specifically, when participants were able to prolong processing in order to implement maintenance strategies (i.e. in the experimenter-led task), memory items would be displaced from primary memory and therefore require (longer) retrieval from secondary memory. Previous research has argued that longer recall times indicate the use of semantic cues to retrieve items from secondary memory; and that this is more evident in sentence-based span tasks (Cowan et al., 2003). Therefore, it was predicted that the relationship between recall times and HLC would only be evident in the experimenter-led (i.e. when processing can be delayed) version of the verbal CST.

2.8.3 Research question three

Do the two additional components of task-switching and inhibition accounted for additional variance in HLC (i.e. non-verbal reasoning, reading and mathematics), over and above that explained by the WM measures?

With regard to the Baddeley and Hitch (1974) model of WM, inhibition and task-switching are key processes in filtering out irrelevant information and enabling attentional focus in WM; and both skills have differently demonstrated predictive relationships with HLC (e.g. Bull & Scerif, 2001; Henry et al., 2012; van der Ven et al., 2013). If time constraints altered the way in which CSTs related to HLC, it was important to identify whether variance in HLC explained by task-switching and inhibition differed depending upon whether WM measures were computer-paced or experimenter-led. Such a finding would be evident in shared or unique variance between WM, inhibition and/or task-switching in predicting HLC.

It was predicted that, consistent with previous research, inhibition and task-switching would be related to academic ability (Bull & Scerif, 2001; Espy et al., 2004; St Clair-Thompson & Gathercole, 2006; van der Sluis, et al., 2007). As there are no existing studies that have examined the relationship between inhibition, task-switching, and WM comparing experimenter-led and computer-paced CSTs, it was unknown what the effect of administration condition would be. However, due to the importance of processing time in the computer-paced tasks (i.e. as identified in Chapter Five), research that has shown links between processing speed and executive control (Rose et al., 2011), and the role of processing speed in HLC (see Fry & Hale, 2000 for a review), there was a possibility that variance accounted for in HLC by task-switching and inhibition over and above contributions from the CSTs, would be affected by administration condition.

2.8.4 Research question four

Can WM at the age of seven- to eight-years predict mathematical ability at the age of nine- to ten-years?

This study examined whether CST mechanisms (storage, processing efficiency, recall times) in Year 3 would predict mathematical ability in Year 5. As the previous three studies, which examined current abilities, collected data throughout the academic year for each cohort it was decided that a lapse of one academic year would be important to ensure sufficient interim learning in, and cognitive maturational development within, the participants prior to assessing longitudinal ability. Therefore, Year 5 (i.e. an entire academic year after the completion *current* ability assessment) was chosen as the time point for longitudinal measurement of maths ability.

Previous research has found verbal WM (Gathercole & Adams, 1994), visuospatial WM (Dumontheil & Klingberg), numerical and visuospatial processing speed (Li & Geary, 2013), and executive control (Bull et al., 2008) to be longitudinal predictors of mathematical ability in primary school children. This study further contributed to this research by investigating whether temporal constraints on the Year 3 WM tasks would identify specific WM abilities (i.e. as identified in Research Question Two) that are important in longitudinal mathematics compared to abilities identified by tasks that have no time restrictions. In addition, the contributions from current executive abilities (i.e. task-switching, inhibition) to longitudinal mathematics performance were assessed.

Based on findings from studies one to three in this thesis, it was predicted that numerical WM (i.e. as demonstrated by Li & Geary, 2013), and visuospatial WM (Dumontheil & Klingberg, 2012) in seven- and eight-year-olds would account for unique variance in mathematical ability in nine- to ten-year-olds. With regard to the longitudinal predictive strength of the computer-paced tasks compared to the experimenter-led tasks, the lack of research in this area made it difficult to formulate a prediction. Therefore, the novel WM measures used in this thesis provided an insight into the longitudinal relationship between WM and mathematics.

2.9 Summary

The current chapter examined existing literature looking at the relationship between WM and HLC. The four principal research questions in this thesis were explained, along with the associated predictions. The following chapter describes the methods used to execute the studies in this thesis, which answer these research questions.

3 Chapter Three: Methodology

This chapter outlines the methodology undertaken for all experiments in this thesis. It includes a description of the sample, design, and details of all measures including reliability. In addition, task procedures and ethical considerations are presented.

3.1 Participants

Participants were recruited from John Ball Primary School and The Pointer School in South-East London. The aim of this research was to assess a representative sample of children in the UK mainstream education system. Therefore, the only exclusion criteria applied was for children with known developmental delays and/or a Special Educational Needs statement. One child left school before they could complete the third testing session and five more children left school before completing any of the testing sessions. In addition, one child was excluded during their second testing session as it was identified that they were colour-blind, and therefore unable to complete three of the tasks (i.e. Dimensional Change Card Sort, Colour-Number Switch, and Raven Coloured-Progressive Matrices). The remaining ninety-two children (41 male, 51 female) aged between seven and eight years of age participated in all five testing sessions included in the first three studies in this thesis. A sub-set of fifty-one children took part in the fourth study in this thesis. All children were unfamiliar with the assessments prior to commencement of testing.

Initially, all participants were assessed on their verbal, and visual and spatial short-term memory and central executive ability to ensure they all performed within the expected range for seven- to eight-year-olds. These constructs are described in detail in section 3.3 but are discussed briefly here before providing details of sample characteristics. Verbal short-term memory, spatial short-term memory and the central executive were assessed using tasks from the Working Memory Test Battery for Children (WMTB-C) (Pickering & Gathercole, 2001). These subtests were Forward Digit Span, Forward Block Span and Backward Digit Span, respectively. Visual short-term memory was measured using the

Visual Sequential Memory task from the Test of Memory and Learning (TOMAL) (Reynolds & Voress, 1994). Table 3.1 gives details of the sample characteristics.

Table 3.1 Summary of means, SDs, ranges for age, standard verbal and spatial short-term memory and central executive measures, and visual short-term memory sub-test scores.

Variable (*n* = 92; 41 boys)	Mean	*SD*	Range
Age at testing session one (in months)	93.95	*4.23*	86-103
Age at testing session five (in months)	97.76	*3.55*	92–107
WMTB-C Digit Span score	111.89	*16.36*	81-160
WMTB-C Block Span score	100.29	*12.85*	70-136
WMTB-C Digit Backwards score	106.23	*106.23*	77-153
TOMAL Visual Sequential Memory score	11.67	*2.89*	5-18

WMTB-C = Working Memory Test Battery for Children; TOMAL = Test of Memory and Learning.

3.2 Ethical Approval and Consent

This study was granted ethical approval from the University Research Ethics Committee, London South Bank University, and was discussed in detail with the relevant senior school staff prior to seeking school and parental consent. Five schools in South-East London were initially contacted by email, and then visited in person by the researcher if a reply of interest was received. After all details of the study were conveyed to ensure understanding of the commitment required by the school, written consent was recorded if given. Letters outlining the study were then sent to all parents of Year 3 children. The letter also included a statement of ethical approval from the University Research Ethics Committee at London South Bank University, and requested parental consent for the child or children to participate. School and parental consent were obtained for all ninety-nine participants to complete the testing sessions. Each child gave verbal consent to participate in the study prior to commencement of the first testing session, and this was digitally recorded by the researcher.

A copy of the consent letter, accompanying information sheet and consent form along with the consent script for the children, can be found in Appendix A.

3.3 Materials

In order to assess the range of cognitive and academic abilities required to answer the four research questions discussed in Chapter Two, twenty separate measures were used in the studies. These were grouped into the cognitive constructs detailed in the following sections. The reliability statistics are provided in Section 3.4.

3.3.1 Short-term memory and the central executive

Three tests from the WMTB-C (Pickering & Gathercole, 2001) and one sub-test from the TOMAL (Reynolds & Voress, 1994) were administered to establish a baseline understanding of the participants' ability to ensure that all participants were performing within the expected range for their age in the areas of verbal short-term memory, visual short-term memory, spatial short-term memory and the central executive. Although the tasks used to measure working memory (WM) in the empirical studies in this thesis were based on standard tasks, they were not standard measures (NB: these are detailed in section 3.3.7).

3.3.1.1 Verbal short-term memory

Verbal short-term memory was measured using the WMTB-C digit recall task. For the digit recall task, the participant was verbally presented with a sequence of digits to be recalled in correct serial order. Digit sequences were designed to appear in random, non-repetitive sequences and spoken at a rate of one digit per second. With six trials per block, trials initially included two numbers and increased by one number in each block until the participant was unable to recall four correct trials in a block. Scores for each trial correct were recorded by applying a value of '1'. The sum of these scores denoted the total score. Within the final block (i.e. point of failure) of trials, a score of '1' was awarded for any trials correctly recalled. No score was awarded for any correctly recalled trials after three errors had been made within a block. All scores were converted to standard scores using the WMTB-C administration manual.

3.3.1.2 Spatial short-term memory

Spatial short-term memory was measured using the WMTB-C block recall task. For the block recall task, the participant was presented with a plastic tray consisting of an array of nine fixed, three-dimensional cubes. The researcher then pointed to a number of cubes in a sequence and the participant was required to point to each of the cubes indicated by the researcher in correct serial order. The locations of the cubes in the sequences were designed to appear random and non-repetitive. Each block was indicated at a rate of one per second. Trials initially included two items and increased by one number in each block until the participant was unable to recall four correct trials in a block. Scoring was similar to that used in the digit span task, wherein a value of ‘1’ was awarded for each trial correctly recalled. The sum of these scores denoted the total score. Within the final block (i.e. point of failure) of trials, a score of ‘1’ was awarded for any trials correctly recalled. No score was awarded for any correctly recalled trials after three errors had been made within a block. All scores were converted to standard scores using the WMTB-C administration manual.

3.3.1.3 Visual short-term memory

Visual short-term memory was measured using the Visual Sequential Memory task from the TOMAL. The participants were presented with abstract designs in a linear array. They were then required to indicate the order in which they were originally presented when given the same designs in a different order. Eight pages of stimuli were presented. The total number of correct positions recalled was recorded. All scores were converted to standard sub-scores using the TOMAL administration manual.

3.3.1.4 The central executive

Central executive ability was measured using the WMTB-C backwards digit recall task. The backwards digit recall task measures the processing and storage of information, as the participant must store the digits presented and reorder them prior to, and during, recall. This procedure requires division and control of attention and allocation of cognitive attention, consistent with the scope of the central executive according to Baddeley (2003; 2007). This task was identical to the digit recall task with the exception that the participant was asked to recall the sequence of verbally presented digits in reverse order. Starting and discontinuation rules, and the scoring procedure were identical to those for the forward digit recall task. All scores were converted to standard scores using the WMTB-C administration manual.

3.3.2 High-Level Cognition

Three measures of high-level cognitive ability were used. Details of each are given below.

3.3.2.1 Non-verbal reasoning

Non-verbal reasoning ability was measured using the Raven's Coloured Progressive Matrices (RCPM, Raven, 2008). In this task, an A4 sized booklet was used to present a total of thirty-six coloured patterns (one on each page). For each pattern, a portion in the bottom right corner was missing. Below the pattern, six pieces (each the same size and shape as the missing piece) were visible. However, only one of them completed the pattern. The participant was required to indicate the piece that completed the pattern above it. The total number correct was recorded. Raw scores were standardised to provide an overall RCPM scaled score.

3.3.2.2 Reading Ability

Reading ability was measured using the Word Reading task from The British Ability Scales third edition (BAS III, Elliot & Smith, 2011). Participants were required to read single words that became progressively more difficult to decode. Testing was discontinued after ten successive reading failures. A single point was awarded for each correctly articulated word. Raw scores were converted to ability scores and then standardised to provide an overall BAS III scaled score.

3.3.2.3 Mathematical ability

Year Three

In the UK, Standard Assessment Tasks (SATs; Kirkup, Sizmur, Sturman & Lewis, 2005) are completed at the end of each Key Stage with the aim of recording attainment in terms of National Curriculum levels. The SATs scores for mathematics assess ability in teaching strands identified by the National Numeracy Strategy (NNS), a framework for teaching mathematics in UK primary schools as dictated by the Department for Education (DfES, 2003). These strands are: number and number system knowledge; calculation; handling data; problem solving; and shape, space and measure. However, Year Three is a non-mandatory SATs testing year in the UK, and a review of potential standard mathematics tests (Access, BAS III Number Skills) with the head mathematics teacher for each school highlighted that learning was not consistent across the schools for Year Three in terms of curriculum content. For example, whereas one school included the teaching of percentages within the calculation strand in Year Three, another school did not teach this until Year 4.

Therefore, due to the differences in curriculum across schools, the use of standardised measures of mathematics ability would almost certainly induce performance differences, not due solely to individual differences in ability, but also due to variations in exposure to certain topics. As an assessment of ability relative to learning opportunities within the UK curriculum was the objective of this measure, it was decided that a standardised mathematics test that did not allow for differences in curriculum content would not provide the correct insight into ability. However, each school chose to assess the children on SATs performance, and the tests were tailored within each school in consideration of the taught topics for that academic year. Hence it was decided that the SATs scores provided by the school would be the best indication of mathematics ability based on learning exposure within the school curriculum. Following a similar approach undertaken in previous studies (Gathercole & Pickering, 2000; Lépine et al., 2005; St Clair-Thompson & Gathercole, 2006), the end-of-year school grades for mathematics for each child for Year Three were acquired from the schools. The grades were awarded by the class teachers, and were based on each child's SATs performance across the NNS teaching strands. The mathematical curriculum is discussed in greater detail in Chapter Seven.

Year Five

The teaching strands for mathematical learning in Year Five are identical to those in Year Three. As dictated by the Department for Education (DfES, 2003), again these strands are: number and number system knowledge; calculation; handling data; problem solving; and shape, space and measure. Before commencing any Year Five maths learning, fifty-one of the children in the first cohort of this research were assessed on their mathematics ability. As the curricular variations identified in Year Three were not apparent, a standardised measure was used. Therefore, Version One of the Access Mathematics Test (McCarty, 2008) assessed ability on the teaching objectives of the national curriculum.

As indicated by the test manual, the assessment was administered as a group test in a classroom. A time limit of fifty-five minutes was allowed. Although a time limit of forty-five minutes is suggested, the manual indicates that an additional ten minutes can be awarded to slow readers without invalidating the test. As optimal assessment of mathematical ability was the aim of the study, this extra time was allowed for those who required it. A total of seven children were awarded the additional ten minutes. Each child was provided with a test booklet, pencil and rubber (as changes to answers were permitted). No calculators, rulers or geometry tools were permitted. One assessor was present for every ten children to ensure that all children worked alone without distraction, copying or discussion. Verbal instruction prior to commencing the test was as follows:

> "It is important that you try your best to answer all questions in this test. However, if there is a question that you do not understand, you may leave it blank. You may find some of the questions easy, but there are some more difficult questions. You may find that the questions get harder toward the end of the test. Please do not worry if you find some questions difficult, but do try your best."

Any child who was not clear about what was required received an additional explanation. This resulted in some children confirming whether or not they could use a ruler when questions relating to the NNS measure strand were approached. However, the number of children requesting this clarification and its impact on test time was negligible. No assistance or cues were provided with regard to the mathematics or language in the questions.

One mark was awarded for each correct answer on the test and attributed to the strand indicated in the booklet. The totals of each strand were then standardised using the administration manual to provide maths age scores and national curriculum levels.

3.3.3 Working memory

Three types of tasks were administered in order to assess functioning in verbal, numerical and visuospatial WM. For the sake of avoiding repetition, and prior to describing the procedure for each WM task, the overall shared design is explained here. As is customary with complex span tasks, the three measures consisted of two common components: processing and storage. All three tasks were administered in two conditions: experimenter-led and computer-paced. Comparison of performance in both conditions was an intrinsic part of this research; therefore, both the experimenter-led and the computer-paced versions were computerised to ensure comparable testing environments. All tasks were presented, either aurally or visually as relevant, via a Dell 5000 Series Inspiron laptop, and were written in E-Prime Version 2.0 (Schneider, Eschman, & Zuccolotto, 2002). In addition, each task was driven by a push-button response box operated by the researcher.

For each task, the participants were first required to complete a series of twenty non-memory trials. This part of the task was used to calculate individual processing speeds for the computer-paced condition in each WM task. It should be noted that, although this procedure was not necessary for the experimenter-led condition, it was still included to ensure consistency of administration experience across both conditions. The non-memory trials consisted of a processing component only, with no requirement for storage. The participants were requested to complete these non-memory trials “as quickly and as carefully as possible". Using counting span as an example, the participants were presented with a screen displaying an array of dots (e.g. seven dots) to be counted out loud. The participant then presented the sum of the count verbally to the researcher. For example, when presented with an array of seven dots, the participant counted out loud; "One, two, three, four, five, six, seven", and then say; "Seven" as the total number. Once the participant articulated the final sum, the researcher pressed the corresponding button on the box to record the response (in this case, "seven"). After the twenty non-memory trials, the program calculated each participant's mean processing speed based on their time taken to engage in the processing tasks and provide a response. Accuracy of 85% was required for inclusion in further assessment. This calculation of 85% accuracy speed was based on the automated OSPAN task developed by Unsworth, Heitz, Schrock, and Engle (2005) for their research into WM capacity. It was designed to ensure that participants were attending sufficiently to the stimuli. However, no participant performed below this ability level. For the experimenter-led version of the task, this calculation was redundant. However for the computer-paced versions, this time, plus 2.5 *sd* was used as a time limit for the processing component of the WM tasks (e.g. counting dots, deciphering the meaning of the sentence and answering 'yes' or 'no', selecting and pointing to the discrepant shape). This calculation of processing speed plus 2.5 *sd* was again based on the automated OSPAN task developed by Unsworth et al. (2005). It was designed to provide the participants with a response window equal to approximately 98% of their individual response values produced in the non-memory trials. For the Listening Span and Odd One Out Span tasks the processing speed was calculated using the mean for all twenty non-memory trials. However, to allow for the variation in speed caused by different quantities of dots on each screen in the Counting Span task, a mean duration was calculated for each of the four different counting screens (i.e. four, five, six or seven dots). To enable this, an equal number of screens per array of dots (i.e. five for each of the four quantities) were presented in the non-memory trials.

For the computer-paced condition, once the participant moved on to the memory-loaded component of the tasks (e.g. count the dots on each screen and recall the totals in correct serial order) the requirement was to complete the processing component within the individual processing time allowance (i.e. mean processing speed plus 2.5 *sd*). If the allotted time was exceeded, the task automatically moved on to the next step (either the next processing item or the recall stage) and that trial was counted as an error. It should be noted that, for the counting span task, the mean (plus 2.5.*sd*) for each quantity count (i.e. four, five, six or seven dots) was applied to the corresponding array in the memory-loaded component of the task.

For each WM task, after the twenty non-memory trials, a practice session was conducted. In these trials, the participants performed the processing component, and were asked to recall the output (e.g. the number of dots) and articulate that output to the researcher once the processing component had ended. The participant was first shown one screen (e.g. an array of dots), asked to perform the processing (e.g. counting out loud and articulating the sum), and provide the output to the researcher. The researcher then recorded this response using the button box. In order to demonstrate the incremental nature of the tasks, there was more than one practice trial, with an increase of one processing item per trial. As minimal expectations for WM span differed across the tasks, there were two incremental trials for both the listening and odd one out span tasks and three for the counting span task.

For the experimenter-led trials, the processing stimulus was presented until a response was given, followed by a 750-millisecond delay, in which a fixation point was displayed on the screen prior to the next processing stimulus being presented. For the computer-paced trials, the processing stimuli were presented for the duration of the individual's mean processing speed, plus 2.5 *sd*. There was then a 750-millisecond delay, whereby a fixation point was displayed on the screen before the next processing stimulus was presented. The participants were required to complete all memory trials correctly during practice before moving on to the measurement task. No child failed to complete this step.

All of the WM tasks were conducted in the same manner in both conditions, with one exception. In the computer-paced condition, the participants were informed of the time restriction. Using the counting span task as an example, the participants were told: “When you see the screen of dots that you need to count, I want you to start counting them straight away as you only have enough time to count them. If you don’t count them straight away, the computer may move on to the next screen before you have finished”. In the actual WM task trials, the timing of the presentation of the stimuli was identical to that described for the practice trials.

3.3.3.1 Numerical working memory

For numerical WM, a counting span measure was developed based on the task of the same name in the WMTB-C. This task may be considered visuospatial due to the requirement to process a visual array of dots. It may also be considered verbal, as the maintenance of information is stored in verbal short-term memory. In addition, it has a considerable numerical element as the processing component requires counting, and the maintenance component requires the storage of numbers. For the purpose of the studies in this thesis, this task is considered a numerical WM task. Following the procedure outlined in section 3.3.7, the processing component of the Counting Span task required the participant to count a number of dots on the computer screen (four, five, six or seven dots) and say the number out loud to the researcher. After a block of six trials, the number of stimulus presentations increased to two screens of dots. This increased incrementally, every six trials, up to seven screens. The participant was asked to recall how many dots were on each screen in serial order. The number of stimulus presentations increased until the participant failed to recall more than three trials out of a block of six. Total trials correct (a maximum of forty-two) represented the participants’ score on this task.

3.3.3.2 Verbal working memory

For verbal WM, a listening span measure was developed based on the task of the same name in the WMTB-C. Following the procedure outlined in section 3.3.7, the processing component of the Listening Span task involved the participant listening to a sentence (e.g. “Apples have noses”), deciding whether or not it made sense and informing the researcher of their decision by saying “yes” or “no” (in this case, “no”). The researcher recorded the response by pressing the corresponding button on the box. The participant was then required to recall the last word of that sentence (in this example, “noses”). The experimenter recorded the responses manually, but pressed a button on the box to indicate that a response had been given. Starting with one sentence per trial, the number of sentences increased across trials to a maximum of seven sentences per trial. The participants were instructed to always recall the last word of the sentences in correct serial order of presentation. The number of sentences per trial increased until the participants were unable to recall more that three trials in a block of six. Total trials correct (a maximum of forty-two) denoted the participant’s score on this task.

3.3.3.3 Visuospatial working memory

For visuospatial WM, an odd one out Span measure was developed based on a similar task created by Henry (2001) to measure non-verbal WM. Following the procedure outlined in section 3.3.7, the processing component of the Odd One Out Span task required the participant to identify, from a horizontal line of three shapes in three separate boxes, which shape was different to the other two. Two of the shapes were always identical whilst a third (in any of the three available positions) was the odd one out. The odd one out was always designed to be definitely identifiable without being immediately obvious. The recall component of this task was to recall where, in the line of three, the odd one out was located, when shown three blank boxes. As with the other WM tasks, the number of odd ones out to identify increased until the participant was no longer able to recall the location of more than three of the relevant shapes, in the correct order, in a block of six. Total trials correct (a maximum of forty-two) denoted the participant’s score on this task.

3.3.4 Inhibition

Inhibition was measured using the Walk/Don’t Walk task from the Test of Everyday Attention for Children (TEA-Ch; Manly, Anderson, Nimmo-Smith, Turner, & Robertson, 2001), and an

3.3.4.1 Walk/Don't Walk

The Walk/Don't Walk (WDW) task from the TEA-Ch required the participant to listen to a series of beeps and take a 'step' (denoted by making a mark with a pen in one of a series of boxes) for each beep. This represented a step down a path (see Appendix B for task sheet). This action was undertaken several times in each trial in order to build a pre-potent response to the sound. However, when a sound was played that was initially similar to the beeps but quickly changed to another, harsher sound, the participant was required to inhibit the pre-potent response of marking a step on the path. This was repeated twenty times, with paths of varying lengths, which were unknown to the participant prior to completing each trial. Therefore they did not know in advance when the harsher sound would occur. The number of correct trials completed throughout the entire task provided the participant's inhibition score.

3.3.4.2 Verbal inhibition

The Verbal Inhibition task consisted of a congruent condition and an incongruent condition. In the congruent condition, the experimenter said the words either 'day' or 'night' out loud and the participant was required to copy by repeating the word. In the incongruent condition, the participants were required to inhibit a copy response and say the alternate word (i.e. if the experimenter said 'day', the participant said 'night' and vice versa). Each of the two conditions consisted of twenty trials and was conducted twice in the following order: copy, inhibit, copy, inhibit. Therefore, a total of eighty trials were conducted. The total time taken to complete the incongruent (i.e. inhibit) condition, as a percentage increase of the total time taken on the congruent (i.e. copy) condition represented the measure of inhibition. (See Appendix C for record and score sheet). The scoring rationale is discussed in more detail in Chapter Six, and in Appendix D.

3.3.4.3 Motor inhibition

The Motor Inhibition task followed the same format as the Verbal Inhibition task. That is, there were twenty congruent trials and twenty incongruent trials, which were repeated alternately resulting in eighty trials. However, for this task the words were replaced with two hand actions (i.e. either an open palm or a closed fist). In the congruent condition, participants were asked to copy the experimenter's hand action by either making an open palm or a closed fist. In the incongruent condition, they were required to do the opposite (i.e. make a closed fist when the experimenter made an open palm, and vice versa). (See Appendix C for record and score sheet). The total number of errors on each task represented the measure of inhibition. The scoring rationale is discussed in more detail in Chapter Six, and in Appendix D.

3.3.5 Task-switching

Task-switching was measured using the Creature Counting task from the TEA-Ch (Manly et al., 2001), the Dimensional Change Card Sort task (DCCS; Zelazo, 2006) and the Colour Number Switch (CNS) which was based on the Trial Making Test (TEA-Ch, 1999) used in previous research (e.g. McLean & Hitch, 1999).

3.3.5.1 Creature Counting

The task featured nine pages presented in a stimulus booklet. On each page, a variable number of "creatures" were shown in a tunnel (see Appendix E). Interposed at varying stages between the creatures were arrows either pointing up or down. The participant was asked to count the creatures from the start of the tunnel beginning with number one, following from left to right "in a zig-zag" and to use the arrows as a trigger to switch the direction of the count (e.g. from counting up to counting down, or vice versa). The booklet had two practice pages that were completed prior to commencing the task in order to establish the participant's ability to count up and down. Each subsequent page was timed. The number of correct items and the time taken to complete each page measured switching ability. Raw scores were converted to ability scores and then standardised to provide an overall TEA-Ch scaled score.

3.3.5.2 The Dimensional Change Card Sort (DCCS)

This task was presented using two small plastic boxes (12cm by 8.5cm by 6cm) with velcro attached to the front. Two laminated target cards (10cm by 10cm), one showing a blue rabbit, the other a red boat were attached to the front of the plastic boxes by velcro back so that they were clearly displayed to the participant throughout the task. In addition, there were two demonstration cards, identical to the target cards except for reversed colours (i.e. red rabbit and blue boat). Twelve standard cards, identical in style to the demonstration and target cards, consisted of three red rabbits, three blue rabbits, three red boats and three blue boats. Six border cards, identical in style to the target and demonstration cards with the inclusion of a 5mm black border around them, consisted of three red rabbits and three blue boats. Finally, six no-border cards, identical to the demonstration and target cards (i.e. no black border) consisted of three red rabbits and three blue boats. All stimuli for this task can be seen in Appendix F. In the demonstration trial the two display panels, with target cards attached, were placed in front of the participant ensuring they were within easy reach. The experimenter sat beside the child so that the display panels were also in the experimenter's view. The child was then told:

> *"Here is a blue rabbit and here is a red boat. Now, we are going to play a card game. This is the colour game. In the colour game, all the blue cards go here (pointing to the blue rabbit display) and all the red ones go here (pointing to the red boat display)."*

The experimenter then showed one of the demonstration cards (i.e. red rabbit) and told the participant:

> *"See, here's a red one, so it goes here."*

The experimenter then placed the card face down in front of the display with the red boat. The child was then shown another demonstration card (i.e. a blue boat) and asked to sort it by colour. If the child sorted the card correctly, they moved on to the pre-switch trial. If the child did not sort the card correctly, the demonstration was repeated until the child understood the rule. In the pre-switch Trial (T1), the child was asked to sort all twelve of the standard cards by colour. The task was timed by the experimenter using a digital stopwatch and any errors were recorded once the task was completed. The child then moved on to the post-switch trial. In the post-switch Trial (T2) the child was told:

> *"Now we are going to play a new game. We are not going to play the colour game anymore. We are going to play the shape game. In the shape game, all the rabbits go here (pointing to the blue rabbit display) and all the boats go there (pointing to the red boat display)."*

The child was then given one of the demonstration cards (i.e. blue boat) and asked:

> *"This is a boat. Where does this one go?"*

After the child had sorted the card they were told, "Let's do another one" and the same procedure was carried out with the other demonstration card. As recommended by Zelazo (2006) this procedure applied regardless of whether or not the child had sorted the card correctly. The child was then asked to sort all twelve standard cards by shape. This task was timed by the experimenter using a digital stopwatch and any errors were recorded once the task was completed. The child then moved on to the border trial. In the border trial, the same target cards were used as in the pre and post switch trials. The child was told:

> *"Now I have a more difficult game for you to play. In this game you sometimes get cards that have a black border around it like this one".*

The experimenter then showed the child one of the six border cards (i.e. red rabbit with a border). The experimenter then told the child:

> *"If you see cards with a black border, you have to play the colour game. In the colour game, red ones go here and blue ones go here."*

The experimenter pointed to the relevant displays. The child was then told:

> *"This card is red so it goes here (i.e. in front of the red boat), but if the cards have no black border, like this one (i.e. red rabbit with no border), you have to play the shape game. In the shape game, if it's a rabbit, we put it here, but if it's a boat we put it there (pointing to the relevant displays). This one is a rabbit so it goes here".*

The experimenter then placed the card in front of the blue rabbit. The child was next asked to sort the six border and six non-border cards, which were provided in a pseudo-random order. As the purpose of the task was to measure switching ability, and not individual differences in the ability to remember task rules, the child was told that they could check what the rule was at anytime during the task. The experimenter timed the task using a digital stopwatch and any errors were recorded once the task was completed. Task-switching ability was scored using the time difference between T2 (post-switch) and T3 (border task), as a percentage of the time score in T2. The scoring rationale is discussed in more detail in Chapter Six, and in Appendix D.

3.3.5.3 The Colour Number Switch (CNS)

The materials for the CNS task consisted of five task sheets per participant. Each of these sheets were A4 size and had printed on them a series of twelve red and twelve blue dots in an irregular pattern across the page. On the first (baseline) sheet, a dotted line connected the blue dots. On the remaining four (test) sheets, the design was the same, except the blue dots were numbered 'one' to 'twelve', as were the red dots. There was also no dotted line connecting the dots on the test sheets. All stimuli for this task can be seen in Appendix G.

In the baseline task (T1), the participant was presented with the baseline task sheet and asked to trace the dotted line "as quickly and carefully as possible" with a pencil. The time taken on this task was recorded using a digital stopwatch and used as a baseline measure of dexterity to identify whether any fine motor deficits were present which could affect task performance. In the first pre-switch blue task (T2) the child was given one of the switch task sheets and asked to ignore all the red dots and just connect the blue dots in number order from 'one' to 'twelve' "as quickly and carefully as possible" with a pencil. The time taken on this task was recorded by the experimenter using a digital stopwatch. In the second pre-switch red task (T3), the child was given another of the switch task sheets and asked to ignore all the blue dots and just connect the red dots in number order from 'one' to 'twelve' "as quickly and carefully as possible" with a pencil. The time taken on this task was recorded by the experimenter using a digital stopwatch. The participant then completed the first of two post-switch tasks. In the red version (T4) they were given another of the switch task sheets and asked to join the dots in number order, starting with the red dot labeled ‘one’ and alternating from red to blue (therefore omitting the red even numbers and blue odd numbers). They were asked to do this “as quickly and carefully as possible” with a pencil. The time taken on this task was recorded by the experimenter using a digital stopwatch. Finally, the post-switch blue task (T5) required the child to repeat the task on a separate sheet but this time alternating from blue to red (therefore omitting the red odd numbers and blue even numbers). They were asked to do this “as quickly and carefully as possible” with a pencil. The time taken on this task was recorded by the experimenter using a digital stopwatch. Task-switching ability was scored using the time difference between the third and fifth stage as a percentage of the time taken in the third stage. This method considered that the second and fourth stage can been viewed as a practice whereby the participant had an opportunity to acquaint themselves with the location of the numbered dots. As such, time delays due to visual searching, as opposed to the required measure of task-switching, should be minimised. The scoring rationale is discussed in more detail in Chapter Six, and in Appendix D.

3.4 Reliability

The reliability statistics for each of the standardised measures and the DCCS, VIMI and CNS measures are shown in Table 3.2.

Table 3.2. Validity and reliabilities data for background, inhibition, and task-switching measures

Measure		Internal Consistency α	Test-retest *r*	Parallel Forms *r*	Age range (yrs)
WMTB-C	Digit Span	-	.81	-	5 – 7
			.82		8 - 10
	Block Span	-	.63	-	
			.43		
	Digit Span Backwards	-	.53	-	
			.71		
TOMAL	Visual Sequential Memory	.84 - .78	.71	-	5 - 59
TEA-Ch	Creature Counting	-	.69 - .73	-	6 - 16
	Walk Don't Walk	-	.73	-	
RCPM	IQ	.97	-	.87	4 - 11
BAS III	Word Reading	.79 - .92	.64	-	3 - 17
AMT	Mathematics	-	.97	-	7 - 12
DCCS		.90 - .94	-	-	3 - 85
CNS		-	.69	-	6 - 16
Verbal inhibition[a]		.68	-	-	5 – 15
Manual inhibition[b]		.81	-	-	5 - 15

WMTB-C = Working Memory Test Battery for Children, TOMAL = Test of Memory and Learning, TEA-Ch = Test of Everyday Attention for Children, RCPM = Raven's Colour Progressive Matrices, BAS III = British Ability Scales version 3, AMT = Access Mathematics Tests, DCCS = Dimensional Change Card Sort (Zelazo,, 2006), CNS = Colour Number Switch; [a], [b:] from Verbal and Motor Inhibition (VIMI; Henry et al., 2012).

Previous research using experimenter-led and computer-paced WM span tasks have produced different findings with regard to their relationship with higher-order cognitive abilities (e.g. Friedman & Miyake, 2004; Lépine et al., 2005; St Clair-Thompson, 2007). Furthermore, although such research has demonstrated the reliability of experimenter-led tasks, very little data exist demonstrating the reliability of computer-paced tasks that account for individual differences in processing speed (but see Unsworth et al., 2005). Although the working memory measures in this thesis are based on tasks that have been demonstrated to be reliable (Daneman & Carpenter, 1980; Gathercole & Pickering, 2000; Henry, 2001; Leather & Henry, 1994), the fact that they have been computerised, in combination with the previous two points, dictates that evaluation of their reliability is advisable.

To assess the reliability of each WM measure, a trial span was calculated for all participants. That is, correct recall on all the first trials were considered (i.e. trial one in Block One, trial one in Block Two, trial one in Block Three etc., up to Block Seven) until the first trial within a block was not correctly recalled. This was repeated for all trial twos, trial threes, etc up to trial six. For example, if a participant recalled the first trials in Block One, Block Two and Block Three, but not in Block Four, they were awarded a score of '3' (i.e. Block One (trial 1) + Block Two (trial 1) + Block Three (trial 1) = 3). A score was allocated based on the sum of all correctly recalled trials (i.e. all first trials across all completed blocks, all second trials across all completed blocks etc.). This total was used to denote a trial span score for each trial. In addition, the total trials correct (TTC) score for each span measure were included. Correlational analyses were conducted on all these scores (i.e. all trial spans and TTC) to estimate reliability (for similar methodology see Henry & MacLean, 2002; Engle, Tuholski, Laughlin, & Conway, 1999). The correlations between each of the measures are shown in Table 3.3. They all indicated moderate to good task reliability (α = .65 to 78). As a further measure of reliability, TTC for each of the six WM tasks were subjected to split-half reliability analysis. Cronbach's alpha across all tasks had high reliability (α = .80). Test-retest analyses between the two version of the counting (α = .72), listening (α = .69) and odd one out (α = .69) span tasks were also robust.

Table 3.3 Correlation between TTC and trial spans for all CSTs showing average correlation and Cronbach's α to indicate reliability

	Span Score (per trial)						
Total Trials Correct	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean (range) *(α)*
Counting EL	.80**	.70**	.73**	.67**	.73**	.73**	.57 (.34-.96) *(.78)*
Counting CP	.75**	.66**	.68**	.60**	.61**	.75**	.50 (.27-.9) *(.77)*
Listening EL	.56**	.54**	.53**	.53**	.37**	.37**	.28 (-.01-.65) *(.65)*
Listening CP	.72**	.65**	.74**	.53**	.73**	.65**	.46 (.17-.74) *(.76)*
Odd one out EL	.66**	.47**	.45**	.56**	.32*	.64**	.33 (-.04-.79) *(.71)*
Odd one out EP	.67**	.51**	.59**	.64**	.67**	.57**	.39 (.16-.68) *(.73)*

EL = Experimenter-led; CP = Computer-paced

$^*p < .05$, $^{**}p < .01$

3.4.1 Data loss

Due to occasional equipment failure with the Odd One Out Span task during the testing phase for the first cohort included in this thesis, some data was not available for analysis. Specifically, sixteen storage scores for the experimenter-led version of Odd One Out Span, and thirteen storage scores for the computer-paced version of Odd One Out Span failed to record due to equipment failure. Therefore, it is noted that the power of any analyses using this data was weaker compared to storage scores from both versions of the Counting and Listening Span tasks (*n* = 92 per task). However, the statistics provided in this section demonstrated that reliability is robust for the experimenter-led (α = .71) and computer-paced (α = .73) Odd One Out Span tasks. A reference to this section is made throughout the thesis whenever this missing data is relevant, and its effect on any findings is noted.

3.5 Procedure

With the exception of the SATs mathematics grades, which were collected from the class teachers at the end of Year Three, the remaining eighteen tasks were administered throughout the Year Three academic year. For each of the 92 participants, the tasks were presented in the same order and every attempt was made to achieve this over five separate sessions. However, interruptions to the sessions due to school activity resulted in some being split further resulting in a total of six shorter sessions for some of the participants. However, single tasks were always completed in one session and the entire session was always completed within two school days. In each school, testing took place in a quiet area away from distractions of other children and teaching activity. Table 4 indicates which tasks were administered in each session. The Access Mathematics Test (McCarthy, 2008) was administered to a sub-set (n = 51) of the participants upon entering Year Five (i.e. two years later).

Table 3.4 Sequence of tasks within each testing session.

Session	Tasks
One	1. Walk/Don't Walk
	2. Creature Counting
	3. Digit Recall
	4. Block Recall
	5. Digit Recall Backwards
Two	6. BAS III Reading
	7. CNS
	8. Counting Span (experimenter-led)
	9. Odd One Out Span (experimenter-led)
	10. Listening Span (experimenter-led)
Three	11. Verbal inhibition
	12. Motor inhibition
	13. DCCS
	14. Visual Sequential Memory
Four	15. Counting Span (computer-paced)
	16. Odd One Out Span (computer-paced)
	17. Listening Span (computer-paced)
Five	18. Raven Colour Progressive Matrices

3.6 Summary

This chapter provided full details of the methodology used in the four empirical chapters included in this thesis. Following is the first of those chapters, which answers the research question: What are the relationships between WM and HLC for computer-paced versus experimenter-led tasks in seven- to eight- year-old children?

4 Chapter Four: Measuring Working Memory: Complex span tasks and the effect of temporal constraints on the relationship with high-level cognition

4.1 Chapter Overview

The research question in this chapter examined the relationships between working memory and high-level cognition in seven- and eight-year-olds. Specifically, the study addressed whether verbal, numerical and visuospatial complex span tasks related to non-verbal reasoning, reading and mathematics differently when processing times were restricted, compared to when they were not. A discussion is provided based on the findings.

4.2 Research Rationale

The literature review in Chapter Two highlighted three important factors. Firstly, previous research has demonstrated that working memory (WM) is related to high-level cognition (HLC) in primary school children; second, processing time is related to storage ability, can mediate opportunities for use of maintenance strategies, and indicate the development of maintenance ability in children, all of which may play a role in the WM-HLC relationship; and finally, restricting processing times in complex span tasks (CSTs) can have domain-specific (i.e. verbal, numerical, visuospatial) effects on relationships with HLC. However, studies investigating the effect of temporal constraints on WM storage, and relationships with HLC have varied in both methodology and findings (see Table 4.1 for a summary) and, as discussed in Chapter Two (see Section 2.5), differences in administration method may explain these discrepancies. More specifically, when generic time restrictions in CSTs have been used to limit processing time allowance (and therefore disrupt maintenance), it is not possible to know whether the effect on the relationship with HLC is due to the time restrictions themselves, or due to individual differences in processing speeds and therefore differences in the ability to cope with these time restrictions.

Table 4.1 *The effect of time constraints on the WM-HLC relationship: A summary of findings from previous research*

	Methodological comparisons			HLC measures				
	PL	EL	CP	Lit	Math	IQ	Higher span score	Stronger predictor
Friedman & Miyake (2004)	✔	✔		✔			non-sig[a]	EL
St Clair-Thompson (2007)	✔	✔		✔	✔		PL	EL
Lépine et al. (2005)	✔		✔	✔	✔		non-sig	CP
Bailey (2012)		✔	✔			✔	CP	non-sig
Lucidi et al. (2014)		✔	✔			✔	non-sig	non-sig

PL = participant-led; EL = experimenter-led; CP = computer-paced; Lit = literacy; [a] = no significant difference between tasks

When investigating WM and HLC at this important stage of cognitive development (see Chapter Two, Section 2.4), any ability to control for individual differences is advantageous in the quest for measurement precision. An extensive review of the current literature has not revealed any research that has utilised individually calculated time restrictions within CSTs in studies of WM and HLC with children. Therefore, this study made a unique contribution to the field of research by measuring WM using novel tasks that account for these individual differences in processing speeds (i.e. computer-paced) and comparing performance to that on CSTs that do not restrict processing times (i.e. experimenter-led).

4.3 Research Question

What are the relationships between WM (i.e. numerical, verbal and visuospatial) and HLC (i.e. non-verbal reasoning, reading and mathematics) for computer-paced versus experimenter-led tasks in seven- to eight- year-old children?

As discussed in Chapter Two (see Section 2.8.1), one view on the relationship between WM and HLC is that WM reflects the ability to coordinate the concurrent processing and storage of information, and that this ability relates to HLC (Baddeley, 1990). An alternative view is that WM reflects the ability to temporarily retain information in memory when a concurrent processing task switches attention away from its maintenance; and that this fundamental attentional capacity relates to HLC (Lépine et al., 2005). An important component of this view is that WM is a rudimentary construct, and that strategy use (e.g. rehearsal) to maintain WM stimuli is unimportant, or even disruptive, in the WM-HLC relationship.

The current study tested these two views of the WM-HLC relationship by using individually titrated CSTs, and comparing performance to that on CSTs where participants controlled their own processing times. The predictions were:

a) If WM is a coordinating ability, then the experimenter-led task should predict HLC, as participants who use strategies to improve WM performance would provide higher span scores, and those participants would perform better on measures of HLC.
b) If CSTs measure a fundamental attentional capacity then the computer-paced tasks, which reduce strategy opportunity, should be better predictors of HLC compared to the experimenter-led tasks. In this latter prediction, higher span scores would represent individuals with a greater attentional capacity, and those participants would demonstrate higher HLC scores.

Consistent with research outlined in Section 2.8.1, the traditional view of WM is that it has a domain-specific element in that information is stored in either a verbal, visuospatial (and possibly numerical) domain dependent on its nature. Therefore, there were also four domain-specific predictions based on this assumption:

a) Visuospatial WM would relate to mathematics ability.

b) Verbal WM would relate to reading and mathematics ability.

c) Numerical WM would relate to mathematics, and possibly reading, ability.

d) Visuospatial WM would related to non-verbal reasoning ability

Finally, research has shown that domain-specific CSTs have been differently affected by restrictions on processing times, as tasks that afford minimal maintenance strategy options (i.e. visuospatial tasks) are not greatly affected when strategy opportunities are reduced. Therefore, it was possible that the relationship between visuospatial WM and HLC would be less affected by administration condition than the other two tasks.

4.4 Method

4.4.1 Design

This study employed a correlational design to determine the relationships between WM and HLC. The data were further analysed using hierarchical regression models to determine the amount of unique and shared variance accounted for in non-verbal reasoning, reading and mathematics by the experimenter-led and computer-paced CSTs[2].

4.4.2 Participants

A total of ninety-two children (41 male, 51 female) participated in all five testing sessions included in the study. None of the children had any known developmental delays, or a Special Educational Needs (SEN) statement. No other selection criteria were applied. All children were unfamiliar with the assessments prior to commencement of testing. The recruitment procedure is provided in detail in Chapter Three.

[2] This methodology was developed based on existing research (Bailey, 2012).

4.4.3 Materials and equipment

The materials and equipment used in all studies in this thesis are described in detail in Chapter Three.

4.4.4 Measures

This study assessed all participants with regard to their individual WM and HLC abilities. Working memory was measured using three CSTs (i.e. numerical, verbal and visuospatial WM). Working memory storage was assessed using both an experimenter-led and a computer-paced administration condition for all three tasks. In addition, all participants were assessed on measures of HLC; namely non-verbal reasoning, reading and mathematics. The specific details of all tasks are set out in Chapter Three.

4.4.5 Procedure

Each participant was tested individually in a quiet room at school, during class times in the school day. Due to the number of tests, assessment was carried out over five sessions. Each session lasted between 30 and 45 minutes, with the exception of the final session in which the non-verbal reasoning measure was administered. The duration of this session was approximately 15 minutes. Occasionally, it was necessary to break a session into two parts due to interruptions such as break-time, lunch, or non-curriculum-related demands (e.g. school play rehearsal, school photograph). However, on such occasions, the testing session was always completed within a single school day.

The tasks were presented in the following order, across the following sessions for all participants. Although the benefits of counter-balancing to lessen order effects were acknowledged, this technique was not applied due to the number of measures administered, which would have resulted in unmanageable logistical challenges. Task order specific to this study is shown in Table 4.2 (overall task order in parenthesis).

Table 4.2 *Sequence of tasks for Chapter Four*

Session	Tasks	Overall sequence
Two	1. BAS III Reading	(6)
	2. Counting Span (experimenter-led)	(8)
	3. Odd One Out Span (experimenter-led)	(9)
	4. Listening Span (experimenter-led)	(10)
Four	5. Counting Span (computer-paced)	(15)
	6. Odd One Out Span (computer-paced)	(16)
	7. Listening Span (computer-paced)	(17)
Five	8. Raven Colour Progressive Matrices	(18)

4.5 Results

With regard to HLC, The RCPM was used to indicate non-verbal reasoning ability; BAS III word reading score was used to indicate reading ability; and end of year SAT maths scores were used to indicate mathematics ability. The SAT scores were awarded to correspond with curriculum grades. These consisted of a number and a letter. To allow for analysis comparable to the other tasks, these were transformed into single numbers representing each level of ability that was assigned as a SAT score (1 = low through to 12 = high ability). These are shown in Table 4.3. Only grades that existed in the data set are shown; therefore the numbers representing mathematical ability range from 6 to 12.

Table 4.3 *SAT maths grades and corresponding scores used to represent mathematical ability*

SAT grade awarded	Corresponding mathematical ability score
2A	6
3C	7
3B	8
3A	9
4C	10
4B	11
4A	12

The mean attainment standardized scores for non-verbal reasoning and reading and mean SAT scores (as indicated by the ability score) for mathematics for this study are shown in Table 4.4.

Table 4.4 *Mean scores, SDs, and ranges for Year 3 HLC measures*

Variable	Measure	Mean	*SD*	Range
Non-verbal reasoning	RCPM	111.2	*16.09*	70-140
Reading	BAS III Reading	110.66	*9.7*	88-128
Mathematics	Year 3 SATs Maths	8.27	*1.37*	6-12

RCPM = Raven Coloured Progressive Matrices, BAS III = British Ability Scales III; SAT = Standard Assessment Tests (Kirkup, et al., 2005)

4.5.1 Performance on working memory tasks

To answer the question as to whether temporal constraints would affect storage capacity in CSTs, mean total trials correct (TTC) for each CST were calculated in both administration conditions. Descriptive statistics for span performance are reported in Table 4.5.

Table 4.5 *Mean TTC, SDs, and ranges CSTs*

	Mean	*SD*	Range
Counting EL	22.10	*4.10*	11-32
Counting CP	22.80	*4.87*	10-34
Listening EL	10.43	*2.92*	4-17
Listening CP	13.30	*3.30*	8-25
Odd One Out EL	13.43	*3.20*	7-20
Odd One Out CP	13.32	*3.00*	8-23

EL = Experimenter-led; CP = Computer-paced

The mean scores for the computer-paced counting span (m = *22*.80, sd = 4.87) and odd one out span (m = 13.32, sd = 3.00) did not differ significantly from the experimenter-led versions (m = 22.10, sd = 4.10), t (89) = 1.61, p = .11 and m = 13.43, sd = 3.20; t (60) = .31, p = .76, respectively). The mean score for the computer-paced listening span (m = 13.30, sd = 3.30) was significantly higher than the mean score for the experimenter-led version (m = 10.43, sd = 2.92), t (90) = 10.43, $p < .001$, d = *.74*).

4.5.2 Correlations between CST performance and measures of HLC

Correlational analysis was conducted to establish the presence of relationships between the CSTs and HLC as a prerequisite for the use of regression (Cohen, Cohen, West & Aiken, 2013). To understand the interrelationships between all of the CSTs and measures of HLC (i.e. prior to investigating predictive relationships), correlation coefficients were calculated for each CST and for non-verbal reasoning, reading and mathematics. All of the CSTs were significantly correlated with each other, with the exception of the experimenter-led versions of the Listening and Odd One Out span tasks. Correlations were highest between the two conditions of the same task type (r = .53 between Counting EL and Counting CP, r = .61 between Listening EL and Listening-CP, r = .59 between Odd One Out EL and Odd One Out

CP). All correlations are presented in Table 4.6. Significant correlations are highlighted in bold.

Table 4.6 *Correlations between all experimenter-led and computer-paced CSTs and HLC measures.*

	1	2	3	4	5	6	7	8
1. Counting EL	-							
2. Counting-CP	**.526****	-						
3. Listening-EL	**.331****	**.333****	-					
4. Listening-CP	**.443****	**.310****	**.613****	-				
5. Odd One Out EL	**.272***	**.337****	.211	**.257***	-			
6. Odd One Out CP	**.386****	**.425****	**.290****	**.399****	**.585****	-		
7. Non-verbal reasoning	**.437****	**.345****	.193	**.263***	.149	**.254***	-	
8. Reading	**.265***	**.275****	**.246***	**.299****	.067	.149	**.311****	-
9. Mathematics	**.613****	**.545****	**.301****	**.432****	.236	**.453****	**.537****	**.485****

EL = Experimenter-led; CP = Computer-paced

* p < .05, ** p < 0.01

Non-verbal reasoning performance was significantly related to performance on the experimenter-led and computer-paced versions of the Counting span task, but only with the computer-paced versions of the Listening and Odd One Out span task. Reading ability was significantly related to performance on both versions of the Counting and Listening span tasks, but to neither of the Odd one out tasks. Finally, mathematics ability was significantly related to both versions of the Counting and Listening tasks, but only the computer-paced version of the Odd one out task.

To understand whether the differences in the magnitude of correlations between computer-paced tasks and experimenter-led tasks in respect of each HLC were significant, *t*-tests were conducted comparing how each CST correlated with non-verbal reasoning, reading and mathematics. There was no significant difference between the experimenter-led correlations and computer-paced correlations on each span task with the HLC measures. Test statistics on the dependent *r*s for these correlations can be seen in Table 4.7.

Table 4.7 *Comparison of dependent rs for experimenter-led and computer-paced CSTs.*

	Non-verbal reasoning	Reading	Maths
Counting span	Z_H = 0.08, *p* = .21	Z_H = -0.21, *p* = .42	Z_H = 0.23, *p* = .41
Listening span	Z_H = -0.26, *p* = .40	Z_H = -0.35, *p* = .36	Z_H = -0.78, *p* = .22
Odd One Out span	Z_H = -0.36, *p* = .36	Z_H = 0.14, *p* = .44	Z_H = 0,42, *p* = .34

4.5.3 Comparisons of variance accounted for in HLC by each CST in each condition

Regression analyses were conducted to evaluate whether experimenter-led and computer-paced span performance measures accounted for the same variance in HLC performance (i.e. non-verbal reasoning, reading and mathematics). Although a small number of outliers were identified in the exploratory analyses (i.e. Kolmogorov-Smirnov, Shapiro-WIlk, Levene's Test), further statistical checks for each regression (Durbin-Watson, tolerance/VIF statistics, Cook's/Mahalanobis distances, plots of standardised residuals/predicted standardised values, standardised residuals, partial plots) did not indicate multicollinearity or cases with undue influence. As a result, a decision was made to include all cases in the final analysis (Field, 2009).

One hypothesis of this study was that if both versions (i.e. experimenter-led and computer-paced) of the span tasks measure the same construct, then HLC performance would be predicted only by variance shared between experimenter-led and computer-paced performance. Conversely, if the two administration methods explained different portions of the variance in HLC, they may account for little or no shared variance in HLC.

To identify the amount of variance in HLC accounted for separately by the computer-paced tasks and experimenter-led tasks, hierarchical regression analyses were conducted for each CST. Therefore, when comparing the predictive power of an experimenter-led task with that of the corresponding computer-paced version with regard to, for example, non-verbal reasoning, the experimenter-led version was entered as step one in the model, then the computer-paced version was entered at step two. This was to determine whether the computer-paced task version still accounted for variance in non-verbal reasoning after controlling for performance on the experimenter-led task. The analysis was then conducted in reverse to determine whether the experimenter-led-version still accounted for variance in non-verbal reasoning after controlling for performance on the computer-paced task. This analysis was repeated for each CST (i.e. Counting, Listening, Odd One Out Span) and HLC measure (i.e. non-verbal; reasoning, reading, mathematics) in turn (see Appendix H for a summary of the processes for each measure).

To address whether HLC performance was predicted by variance shared between the two conditions, linear regression analyses was conducted separately for the Counting, Listening and Odd One Out Span tasks for each measure of HLC. This was calculated using a method employed by Bailey (2012). That is, the computer-paced and experimenter-led versions of each task were entered into a regression model together to calculate how much total variance in each HLC measure was explained by both tasks. The amount of unique experimenter-led variance, and the amount of unique computer-paced variance were then subtracted from the total variance. The resulting amount of variance was interpreted as the variance shared between the two tasks.

4.5.3.1 Non-verbal reasoning

4.5.3.1.1 Counting Span

Performance on the two Counting Span tasks together predicted non-verbal reasoning (F (2, 87) = 11.6, p < .001); and the amount of total variance accounted for in non-verbal reasoning by both task was 21% (R^2 = .211, p < .001). Looking at the tasks individually, the experimenter-led version accounted for a significant amount of variance in the presence of the computer-paced version (β = .35, p < .005). However, performance on the computer-paced version of the counting span task did not predict non-verbal reasoning in the presence of the experimenter-led task (R^2 change = .02, p = .15). The amount of variance accounted for by the experimenter-led task and the amount accounted for by the computer-paced task were subtracted from the total variance (i.e. .21 - .02 - .089 = .10). Variance shared by both Counting Span tasks was 10%. Therefore, around half of the variance explained in non-verbal reasoning performance was shared between the two versions of the Counting Span task.

4.5.3.1.2 Listening Span

Although performance on the listening span tasks significantly predicted non-verbal reasoning when entered together (F (2, 88) = 3.34, $p < .05$), the experimenter-led version did not account for variance in the presence of the computer-paced version, and vice versa. The computer-paced task predicted non-verbal reasoning when *not* controlling for the performance on the experimenter-led task (R^2 = .07, $p < .05$). The amount of total variance accounted for in non-verbal reasoning by both versions of the Listening Span task was 7% (R^2 = .07, $p < .05$). The amount of variance accounted for by the experimenter-led task and the amount accounted for by the computer-paced were subtracted from the total variance (i.e. .07 - .034 - .002 = .034). Variance shared by both Listening Span tasks was 3.4%. Therefore, around half of the variance explained in non-verbal reasoning performance was shared between the two versions of the Listening Span task.

4.5.3.1.3 Odd One Out Span

The model assessing variance explained in non-verbal reasoning from both versions of the odd one out span task was not significant (F (2, 59) = 1.1, p = .34). As the model was not significant, no shared or unique variance was calculated.

The information in Table 4.8 includes total variance accounted for in non-verbal reasoning (total R^2), changes in R^2, standardised β-values, and F Changes for each predictor variable. Significant values are indicated in bold and by asterisks where relevant.

Table 4.8 *Summary of hierarchical regressions for CSTs predicting non-verbal reasoning ability.*

Predictor variable	**Total R^2**	**Change in R^2**	**β**	***F* Change**
Counting	**.21*** **			
Step 1: EL		**.19*** **	**.35** **	**20.82*** **
Step 2: CP		.02	.17	2.16
Step 1: CP		**.12** **	.17	**12.22** **
Step 2: EL		**.09** **	**.35** **	**9.81** **
Listening	**.07***			
Step 1: EL		.04	.05	3.40
Step 2: CP		.03	.23	3.19
Step 1: CP		**.07***	.23	**6.60***
Step 2: EL		.002	.05	0.15
Odd One Out	.04			
Step 1: EL		.02	.06	1.32
Step 2: CP		.01	.15	0.87
Step 1: CP		.03	.15	2.07
Step 2: EL		.002	.06	0.15

EL = Experimenter-led; CP = Computer-paced

$^*p<.05$; $^{**}p<.01$; $^{***}p<.001$

4.5.3.2 Reading ability

4.5.3.2.1 Counting Span

Performance on both the counting span tasks together significantly predicted reading ability (F (2, 87) = 4.7, $p < .05$). No variance in reading ability was accounted for by the experimenter-led task in the presence of the computer-paced task, and vice versa. However the experimenter-led task ($R^2 = .07$, $p < .05$) and the computer-paced task ($R^2 = .08$, $p < .05$) both accounted for variance in reading ability in isolation. The amount of total variance accounted for in reading by both versions of the Counting Span task was 10% ($R^2 = .10$, $p < .05$). The amount of variance shared by both counting span tasks was 5.1%. This was calculated using the same method described in section 4.5.3.1 (i.e. .097 - .026 - .02 = .051). Therefore, just over half of the variance explained in reading ability was shared between the two versions of the Counting Span task.

4.5.3.2.2 Listening Span

Performance on the Listening Span tasks together significantly predicted reading ability (F (2, 88) = 4.58, $p < .05$), but neither version accounted for significant variance in reading ability in the presence of the other task. However the experimenter-led task ($R^2 = .06$, $p < .05$) and the computer-paced task ($R^2 = .09$, $p < .01$) both predicted reading ability in isolation. The amount of total variance accounted for in reading by both versions of the Listening Span task was 9% ($R^2 = .09$, $p < .05$). The amount of variance shared by both Listening Span tasks was 5.2%. This was calculated using the same method described in section 4.5.3.1 (i.e. .094 - .04 - .005 = .049). Therefore, just over half of the variance explained in reading ability was shared between the two versions of the listening span task.

4.5.3.2.3 Odd One Out Span

The model to assess whether both versions of the Odd One Out Span task accounted for variance in reading ability was not significant (F (2, 59) = 0.94, $p = .40$). As the model was not significant, no shared or unique variance was calculated.

The information in Table 4.9 includes total variance accounted for in reading ability (total R^2), changes in $R^{2,}$ standardised β-values, and *F* Change for each predictor variable. Significant values are indicated by an asterisk where relevant.

Table 4.9 *Summary of hierarchical regression for CSTs predicting reading ability.*

Predictor variable	**Total R^2**	**Change in R^2**	**β**	***F* Change**
Counting	**.10***			
Step 1: EL		**.07***	.17	**6.66***
Step 2: CP		.03	.19	2.53
Step 1: CP		**.08***	.19	**7.33***
Step 2: EL		.02	.17	1.89
Listening	**.09***			
Step 1: EL		**.06***	.09	**5.41***
Step 2: CP		.04	.24	3.59
Step 1: CP		**.09****	.24	**8.76****
Step 2: EL		.005	.09	0.49
Odd One Out	.03			
Step 1: EL		.009	-.02	0.47
Step 2: CP		.02	.18	0.25
Step 1: CP		.03	.18	1.90
Step 2: EL		<.001	-.02	0.009

EL = Experimenter-led; CP = Computer-paced

* *p* <.05; ** *p* <.01; ****p* <.001

4.5.3.3 Mathematics ability

4.5.3.3.1 Counting Span

The model predicting mathematics ability was significant (F (2, 87) = 34.7, p < .001). Both the experimenter-led (β = .45, p < .001) and the computer-paced (β = .31, p < .005) versions of the Counting Span task accounted for variance in mathematics ability in the presence of the other task. The amount of total variance accounted for in mathematics ability by both versions of the Counting Span task was 44% (R^2 = .44, p < .001). The total variance shared between both Counting Span tasks in was 22.9%. This was calculated using the same method described in section 4.5.3.1 (i.e. .444 - .147 - .068 = .229). Therefore, around half of the variance explained in mathematics ability was shared between the two versions of the Counting Span task.

4.5.3.3.2 Listening Span

For the Listening Span task, the model predicting mathematics ability was significant (F (2, 88) = 10.45, p < .001), with performance on the computer-paced version accounting for variance (β = .39, p < .005) in the presence of the experimenter-led version. The experimenter-led task did not predict mathematics ability in the presence of the computer-paced task (change in R^2 = .002, p = .61). The amount of total variance accounted for in mathematics ability by both versions of the Listening Span task was 19% (R^2 = .19, p < .001). The amount of variance shared by both Listening Span tasks was 9%. This was calculated using the same method described in section 4.5.3.1 (i.e. .189 - .097 - .002 = .09). Therefore, just under half of the variance explained in mathematics ability was shared between the two versions of the Listening Span task.

4.5.3.3.3 Odd One Out Span

The overall model for the Odd One Out span was significant (F (2, 59) = 8.09, p < .01). The computer-paced version accounted for a significant amount of variance in mathematics ability (β = .49, p < .005) in the presence of the experimenter-led version. The experimenter-led version did not account for a significant amount of variance in the presence of the computer-paced task (change in R^2 = .001. p = .77). The amount of variance shared by both Odd One Out span tasks was 5.8%. This was calculated using the same method described in section 4.5.3.1 (i.e. .215 - .156 - .001 = .058). Therefore, just over one quarter of the variance explained in mathematics ability was shared between the two versions of the Odd One Out span task.

The information in Table 4.10 includes total variance accounted for in mathematics ability (total R^2), changes in $R^{2,}$ standardised β-values, and F Change for each predictor variable. Significant values are in bold and indicated by an asterisk where relevant.

Table 4.10 *Summary of hierarchical regression for CSTs predicting mathematics ability.*

Predictor variable	**Total R^2**	**Change in R^2**	**β**	***F* Change**
Counting	**.44*** **			
Step 1: EL		**.38*** **	**.45*** **	**52.88*** **
Step 2: CP		**.07** **	**.31** **	**10.72** **
Step 1: CP		**.30*** **	**.31** **	**37.13*** **
Step 2: EL		**.15*** **	**.45*** **	**23.10*** **
Listening	**.19*** **			
Step 1: EL		**.09** **	.06	**9.02** **
Step 2: CP		**.10** **	**.39** **	**10.52** **
Step 1: CP		**.19*** **	**.39** **	**20.41*** **
Step 2: EL		.002	.06	0.26
Odd One Out	**.22** **			
Step 1: EL		.06	-.04	3.76
Step 2: CP		**.16** **	**.49** **	**11.75** **
Step 1: CP		**.21*** **	**.49** **	**16.34*** **
Step 2: EL		.001	-.04	0.88

EL = Experimenter-led; CP = Computer-paced

** $p < .01$; *** $p < .001$

4.5.4 The relationship between all CSTs and HLC ability

To understand how all six measures of WM relate to HLC, both versions of the Counting, Listening and Odd One Out Span tasks were entered into a regression model to predict non-verbal reasoning, reading and mathematics in turn.

4.5.4.1 Non-verbal reasoning

The overall model predicting non-verbal reasoning ability was significant (F (6, 83) = 4.06, $p < .01$), accounting for 23% of variance ($R^2 = .227$, $p < .01$). The experimenter-led version of Counting Span task was the only task with a significant β value (β = .32, $p < .01$).

4.5.4.2 Reading

The overall model predicting reading ability was significant (F (6, 83) = 2.39, $p < .05$), accounting for 15% of variance ($R^2 = .147$, $p < .05$). None of the tasks, taken in isolation, had a significant β value.

4.5.4.3 Mathematics

The overall model predicting mathematics ability was significant (F (6, 83) = 12.50, $p < .001$), accounting for 48% of the variance ($R^2 = .475$, $p < .001$). Both the experimenter-led (β = .38, $p < .001$) and the computer-paced (β = .30, $p < .01$) versions of Counting Span had significant β values. There were no other significant β values.

The information in Table 4.11 includes total variance accounted for in mathematics ability (total R^2), and standardised β-values for each predictor variable. Significant values are in bold and indicated by an asterisk where relevant.

Table 4.11 *Summary of linear regression for all CSTs tasks predicting HLC*

	Non-verbal reasoning	**Reading**	**Mathematics**
Total R^2	**.23****	**.15***	**.48*****
Predictor variable	**β**	**β**	**β**
Counting			
Experimenter-led	**.32****	.09	**.38*****
Computer-paced	.11	.20	**.30****
Listening			
Experimenter-led	.003	.13	.0
Computer-paced	.01	.17	.18
Odd One Out			
Experimenter-led	.04	.06	.08
Computer-paced	.11	.10	.10

** $p < .01$; *** $p < .001$

4.6 Discussion

The current study investigated the effect of time-constraints on CSTs and the subsequent relationships with HLC. Despite the drop in span score in both the Counting and Odd One Out Span tasks, this did not reach statistical significance. Previous research with adults has found that restricting processing times in CSTs results in a restriction on maintenance opportunity (e.g. rehearsal) and a related decrease in span score (e.g. St Clair-Thompson, 2007). The reason for this not occurring in the current study is unclear, but given the age of the sample (i.e. seven- to eight-year-olds) and research evidence that maintenance strategies such as rehearsal (Gathercole & Hitch, 1993; Gathercole, Adams, & Hitch, 1994; Henry & Millar, 1991; 1993) and refreshing (Barrouillet & Camos, 2001; Barrouillet et al., 2009; Camos & Barrouillet, 2011), emerge at approximately seven years of age, it is possible that the use of maintenance strategies was inconstant across the sample. This may not have produced an effect sufficient enough to create a significant reduction span scores in the computer-paced condition.

Mean scores for computer-paced Listening Span were significantly higher than mean scores for the experimenter-led version. The stimuli used for the processing components of the experimenter-led and computer-paced tasks were identical (see St Clair-Thompson, 2007, for a similar methodology). Identical stimuli were used in order to minimise variation in ability caused by differing processing demands that may have arisen from using different stimuli (St Clair-Thompson, personal communication, 11 February 2015). Due to the semantically meaningful nature of sentences, it is possible that some of the sentences were retained in long-term memory from the experimenter-led trials administered twelve weeks earlier (see Cowan et al., 2003 for a similar explanation for longer recall times in a sentence span task). Therefore, practice effects may have occurred for this particular task. This could then have resulted in faster processing of the stimuli, leaving more time for maintenance of memory items, which could have led to higher span scores. However, the computer-paced tasks were individually titrated based on response times in processing stimuli akin to those used in the CSTs, and this was undertaken immediately before the task was executed. Therefore, if the participants were processing the stimuli faster due to familiarity, this would have been reflected in the calculation of their individual processing times and any practice effects should have been greatly reduced in the titration process. This should have minimised the effect of faster processing in the computer-paced sessions. Therefore, although the reason for higher span scores may be rooted in practice effects, it is noted that there are possibly other underlying, undetermined reasons.

Multiple correlations were found across the CST storage scores and measures of HLC. Notably, only six out of the thirty-six *r* values did not reach significance. It is understood that this may raise concerns regarding the reliability of the results. However, it is already understood that CSTs relate strongly to HLC (e.g. Hitch et al., 2001), so such consistent correlations were expected. In addition, it would be surprising if performance between the

CSTs were not interrelated in a typical population (i.e. one in which there were no expectations of domain-specific deficits). The purpose of correlational analysis in the current chapter (and in subsequent chapters in this thesis) was to establish that there were relationships between the CSTs and HLC to establish rationale for the use of regression (Cohen et al., 2013). Therefore, interpretation of the results in this study and the thesis as a whole are not based on correlational analysis. Rather, this method has been used as a stepping-stone to multiple regressions in order to predict performance on measures of HLC.

Results showed that for Counting and Listening Span, approximately half of the variance accounted for in each of the HLC measures was consistently shared between the two administration conditions (i.e. experimenter-led and computer-paced). However, the two versions of the Odd One Out Span task shared approximately 25% of the variance in HLC, and this was with regard to mathematics ability only (i.e. Odd One Out Span did not account for a significant amount of variance in non-verbal reasoning or reading ability). The existence of shared variance across administration conditions in Counting and Listening Span for all three HLC measures and in Odd One Out Span for mathematics ability indicates that the two administration conditions tap both similar, and different cognitive abilities.

Regression analyses showed that Counting Span was a strong predictor of non-verbal reasoning and mathematics ability in isolation from Listening and Odd One Out Span (i.e. in a model on its own). Also, with regard to non-verbal reasoning and mathematics, Counting Span was the only predictor with a significant β value when placed in a regression model with both versions of the Listening and Odd One Out Span tasks. It could be argued that the processing stimuli in Counting Span (i.e. counting a small array of dots with no distractors) created a lower cognitive load than comprehending sentences in Listening Span and deciphering shapes in Odd One Out Span (see Lépine et al., 2005 for a similar perspective). Therefore the finding that Counting Span was a predictor of non-verbal reasoning and mathematics ability compared to Odd One Out and Listening Span can be interpreted as consistent with the view that WM is a rudimentary attentional resource (e.g.

Lépine et al., 2005) and that CSTs that use simple processing stimuli (e.g. reading out single letters) are better predictors of HLC than CSTs that use more complex processing items (e.g. reading sentences). Consistent with previous research (e.g. Cowan et al., 2003) these findings may indicate that span tasks that use more complex stimuli can be affected by individual differences in higher-order cognitive abilities (e.g. comprehension).

However, Lépine et al. (2005) used time restrictions on these simpler tasks when comparing them to traditional, more complex span tasks based on the view that a reduction in strategy opportunity strengthens the WM-HLC relationship. Their interpretation of the findings was that it was a combination of the simplicity of the timed tasks, and the restrictions they placed on maintenance opportunities that created stronger relationships with HLC. In the current study, it was the experimenter-led version of the Counting Span task that led to higher scores compared to the computer-paced version. This comparison was not available in the study by Lépine et al. as non-time constrained versions of the simpler tasks were not used. Therefore, the findings from the current study may indicate that the simplicity of stimuli can strengthen the link with HLC without a requirement for time restrictions, and that maintenance strategies may not disrupt the WM-HLC relationship.

With regard to reading, both versions of the Counting and Listening Span tasks predicted ability. Both of these tasks can be said to measure verbal WM, which has been shown to be a good predictor of reading comprehension (Oakhill et al., 2011). Therefore, this finding is expected. However, neither administration condition for the tasks showed any advantage over its counterpart with regard to predictive strength (i.e. no significant change in R^2 when the computer-paced version was entered into the model after controlling for the experimenter-led version, and vice versa). This result was inconsistent with other studies that have found timed-tasks to be more predictive of reading ability in adults (Friedman & Miyake, 2004; St Clair-Thompson, 2007) and literacy in children (Lépine et al. (2005). However, with regard to mathematics ability, the computer-paced Listening Span task was a better predictor than the experimenter-led version. Therefore, whereas the relationships between reading and Counting Span, and reading and Listening Span were relatively unaffected by time-constraints, the computer-paced condition strengthened the relationship with mathematics for Listening Span but not for Counting Span. It is possible that Lépine et al. (2005) identified two separable factors in the relationship between CSTs and HLC; the first being that simple tasks are more predictive (i.e. as indicated by Counting Span with regard to non-verbal reasoning and mathematics); and the second being that timed tasks can strengthen the relationship between CSTs and HLC (i.e. as indicated by Listening Span with regard to mathematics and, to a lesser degree, non-verbal reasoning). The finding that the relationship between Odd One Out Span and mathematics ability was only significant in the computer-paced condition further supports this conclusion.

4.7 Executive summary

The purpose of this chapter was to examine the effect of time constraints on CST performance and the relationship with HLC. Time-restrictions on CSTs did not affect span scores and this may be due to an inconsistent development of maintenance strategies across the sample due to variations in ability at this stage of development. The computer-paced tasks did relate to measures of HLC differently compared to the experimenter-led tasks. However, this was not consistent for all of the WM measures (i.e. numerical, verbal, visuospatial), nor for all of the HLC measures (i.e. non-verbal reasoning, reading, mathematics). Generally, Counting Span in the experimenter-led condition predicted HLC. However, Listening Span and Odd Out Span predicted mathematics ability, but this was only evident when tasks were time-constrained. Explanations of the varying influences (or lack thereof) of administration condition on the relationship between WM and HLC are limited without further investigating the underlying mechanisms of CSTs. Chapter Five examines the respective roles of processing time, processing accuracy, recall timing, and storage in the WM-HLC relationship.

5 Chapter Five: Processing time, processing accuracy, recall time and storage in complex span tasks

5.1 Chapter Overview

The previous chapter demonstrated that temporal constraints within complex span tasks influence the relationship between working memory and high-level cognition. The research questions in the current chapter investigated the underlying mechanisms involved in complex span task performance in addition to storage; namely, processing time, processing accuracy, and recall time. The research question was – are these underlying mechanisms differentially affected by administration condition, and does this influence their relationship with high-level cognition?

5.2 Research Rationale

According to both the multi-component (Baddeley & Hitch, 1974) and the TBRS (Barrouillet et al., 2004) models of WM, time restrictions on CSTs affect the domain-general processing component of WM and possibly limit the domain-general construct of active maintenance. Therefore, when there are no time restrictions, longer processing times should relate to higher storage scores as time for maintenance strategies is permitted. However, Chapter Four showed that time restricted tasks did not result in lower span scores, but placing time restrictions on complex span tasks (CSTs) did affect the relationship with high-level cognition (HLC). Therefore, it is possible that processing times were increased in the computer-paced tasks in order to maintain storage capacity. Should this ability be important in HLC, the participants who were able to achieve this increase in processing speed would also perform better on measures of HLC.

Chapter Four also found different effects of time restrictions for Counting, Listening and Odd One Out Span, suggesting that manipulations of domain-general processing can have domain-specific effects. In addition to the effect of time restrictions on processing times, it is possible that the computer-paced tasks affected how memoranda were stored, and that this was dependent on WM domain. For example, when participants were potentially prolonging processing in order to implement maintenance strategies (i.e. in the experimenter-led task), memory items may have been displaced from primary memory and therefore required retrieval from secondary memory, which may take more time (i.e. evident in recall duration). Previous research has suggested this to be specific to sentence-based span tasks (Cowan et al., 2003), and that recall times, along with span scores, can be used to predict HLC (see Section 2.6). Therefore the current study also examined the effect of time-restrictions on recall times in the Listening Span task, and subsequent relationships with HLC.

Also, the study in Chapter Four found Counting Span to be the only predictor of reading and non-verbal reasoning ability, and that this task was unaffected by time constraints. This provided support for the TBRS model, which argues that processing stimuli in CSTs need not be complex, but simply switch attention away from memoranda, long enough to cause decay (e.g. Lépine et al., 2005). The current chapter investigated the effect of time constraints on processing accuracy within each CST to identify whether stimuli is differently affected dependent on its complexity. In addition, it was of interest to establish whether processing time and processing accuracy were differently affected by time constraints. The resource-sharing hypothesis of WM is that processing time and accuracy are a single resource (see Section 1.3.1). If this is the case then they should be similarly affected by time constraints. However, the view has been challenged by studies that have shown processing time and accuracy to have separate influences on HLC (e.g. Bayliss et al., 2003; 2005; Unsworth et al., 2009; see Section 2.2.1). Therefore, the current study examined processing accuracy, separate from processing time across three CSTs in two different administration conditions. Should processing time and accuracy be differently affected by administration condition, this would support the view that they are indeed separate constructs (e.g. Bayliss et al., 2003) and the finding would, therefore, challenge to resource-sharing model of WM.

To summarise, the study in this chapter examined the relationships between processing time, processing accuracy, recall time, and storage capacity in CSTs; and investigated whether these separate underlying mechanisms related to each other, and to HLC differently when the time allowed for the processing component of the task was restricted (i.e. computer-paced) compared to when it was not (i.e. experimenter-led). There are no existing studies that have examined the effect of individually titrated time restrictions on all four of these CST mechanisms in primary school children. Moreover, no studies have investigated how such temporal constraints affect each of these mechanisms when viewed as individual predictors of HLC. Identifying the mechanisms that underlie CST performance and how they link to HLC can inform understanding of how and why children progress at varying rates academically. This information can then be used in learning and intervention programs in schools.

5.3 Research Questions

Do the separate mechanisms employed in CSTs (i.e. storage, processing time, recall time and processing accuracy) relate to each other, and to HLC, differently when the time allowed for the processing component of the task is restricted compared to when it is not?

The predictions for the current study were:

a) Faster processing times in the computer-paced tasks would link to higher storage scores indicating an increase in speed to prevent decay; whereas slower processing times in the experimenter-led task would relate to higher storage scores indicating the use of maintenance strategies to preserve memory items.

b) Processing accuracy within each CST would be differently affected by time-constraints dependent on its complexity. Specifically, in the computer-paced condition compared to the experimenter-led condition, processing accuracy in the Listening Span task would decrease to a greater degree compared to the Odd One Out Span task; and processing accuracy in the Odd One Out Span task would decrease to a greater degree compared to the Counting Span task.

c) With regard to the effect of time restrictions on processing accuracy compared to processing time, due to the scarcity of research in the area it was not possible to predict the direction of the effect; however it was predicted that processing accuracy would be differently affected by time-constraints compared to processing time, and that the two mechanisms would relate to each other differently in the two administration conditions. This would indicate that processing time and accuracy are separate constructs.

d) In the computer-paced tasks an increase in processing speed (compared to that in the experimenter-led condition) would be required to prevent decay of information in WM, and that children who could process stimuli faster to achieve this would also score higher on measures of HLC.

e) Faster recall times in the experimenter-led version of the verbal WM task would relate to higher HLC skills indicating that an ability to retrieve information from secondary memory quickly is linked to HLC.

5.4 Method

5.4.1 Design

This study employed a correlational design to determine the effect of temporal constraints on: (1) the mechanisms underlying CSTs; and (2) their relationships to HLC. The aim was to identify which underlying CST mechanisms explained unique variance in HLC. The relationships between CST span scores (i.e. storage) and HLC were identified in Chapter Four. The current study used forced entry hierarchical regression to determine which CST mechanisms predicted unique variance in each HLC measure over and above storage. These analyses were conducted for each CST in both the experimenter-led and computer-paced CST conditions.

5.4.2 Participants

The sample for this study was the same as that used in Chapter Four. All children were unfamiliar with the assessments prior to commencement of testing.

5.4.3 Measures

This study assessed all participants with regard to their individual WM and HLC abilities. Working memory was measured using three CSTs; Counting Span, Listening Span and Odd One Out Span. Each task was administered in both an experimenter-led and a computer-paced condition.

Performance on the CSTs was fractionated further to create scores for processing time, recall time, and processing accuracy. Processing time was calculated based on the duration in milliseconds from presentation of stimuli to provision of a response (e.g. final count in the case of Counting Span). Consistent with the marking protocol for WMTB-C, upon which this task was based, processing times were not dependent on the accuracy of the response. Therefore, processing times for all completed trials were calculated. Processing accuracy was calculated based on the number of correct responses within each trial.

Recall time was calculated as total trial duration divided by number of items in that trial. This was done for all responses regardless of error. It is acknowledged that there was a risk that this could include random responses such as ‘guesses’; however, all responses were also recorded manually and a review of these data showed that any errors were ones of incorrect order or a failure to remember an item at all. Use of the more conservative method of recording recall times only for correct responses was considered, but rejected as problematic due to the method of calculation (i.e. total time taken in the recall phase of the task, divided by the number of items in the list). Had incorrect responses been excluded, then the recall time would have been misrepresentative of the time taken on that part of the task.

The CSTs designed for this thesis were all computer-administered using a laptop for ease of portability. As discussed in Chapter Three, a button box was attached so that the experimenter could record all responses whilst the participant had full view of the laptop screen. Although this method was practical in these terms, use of the button box limited the amount of information that could be collected for the Listening Span task. As it was intended that the actual response per trial be recorded (i.e. the word spoken as opposed to correct or incorrect), the Listening Span recall items were recorded manually, with complete recall being indicated by a single push of a button on the box at the moment the last responses had been given. Therefore only overall response durations, and not inter-word pauses, were possible for this task. As a result, it was only possible to review recall times at a macro level for Listening Span. To ensure consistency across all CSTs, this same method of measurement was also used for Counting and Odd One Out Span.

Precise calculations for these performance indices can be seen in Section 5.5.1. In addition, all participants were assessed on measures of HLC; namely non-verbal reasoning, reading and mathematics. The specific details of all tasks are set out in Chapter Three.

5.4.4 Procedure

All the participants were tested in a quiet room at school, during class times in the school day. Full details of the testing sequence can be found in Chapter Three.

5.5 Results

Due to the number of variables in this chapter (i.e. CST: Counting, Listening, Odd One Out Span; CST mechanisms: storage, processing time, recall time, processing accuracy; HLC measures: non-verbal reasoning, reading and mathematics), the α level for significance was reviewed to minimize the risk of Type One errors. As a Bonferroni adjustment was considered too conservative given the number of measures (Bland & Altman, 1995), a decision was made to set the α level at p <.01 (for a similar methodology see Geary et al., 2007).

5.5.1 Calculation of performance indices

Due to individual differences in span scores, not all participants progressed equally far through the seven blocks of trials that make up the CSTs. Therefore, for recall timing, processing time, and processing accuracy, some participants only produced data for the first three blocks of trials before their participation was discontinued due to failure to successfully recall more than three trials in a block (i.e. as per the administration rules). In order to ensure that all cases were included in the analysis, only data for blocks one to three were included for each of the span tasks. Performance indices for each CST mechanism were then calculated as follows; the values for processing time and recall time were first converted to z-scores to identify any values more than 2.5 standard deviations from the mean. The corresponding true values (i.e. as opposed to z-scores) of the scores that were more than 2.5 standard deviations above the mean (no values greater than 2.5 standard deviations *below* the mean were identified) for each individual item were winsorized and substituted with the upper criterion value for that item. This resulted in the alteration of approximately 9.7% of responses in Counting, Listening and Odd One Out Span for the recall and processing times (for similar methodology see Bayliss et al., 2003; 2005). This process was undertaken to remove the influence of any extreme responses as recommended by Ratcliff (1993). Winsorizing was not required for the processing accuracy values as these were reported as proportions and were, by definition, all within the upper and lower criterion values. The performance index for storage was total trials correct (TTC) across all blocks consistent with that used for the study in Chapter Four. This was to ensure that maximum storage ability was reflected in the analyses as an indication of ability.

5.5.2 Trial by trial performance analysis

As only the first three blocks in each span task were used to calculate processing time, recall time and processing accuracy performance indices, it was necessary to determine whether performance differed significantly between Counting, Listening and Odd One Out Span across blocks in each administration condition. For example, should a time-based score (i.e. processing or recall time or processing accuracy) increase or decrease significantly from one block to another in one CST but not another, this could indicate inconsistencies in the calculation of performance indices. Therefore, a series of 3 x 2 x 3 repeated measures analyses of variance (ANOVA) were conducted to examine the effect of task (i.e. Counting, Listening, Odd One Out), condition (i.e. experimenter-led and computer-paced) and block (i.e. 1,2,3) on processing times, recall times and processing accuracy.

For processing times, there was no significant main effect of task (F (2,100) = .160, p = .852), condition (F (1,50) = .012, p = .913) or block (F (2,100) = .011, p = .989). Recall times demonstrated no main effect of task (F (2,104) = .109, p = .897), condition (F (1,52) = .096, p = .758) or block (F (2,104) = 3.290, p = .041)[3]. Finally, processing accuracy showed no main effect of task (F (2,106) = .881, p = .417), condition (F (1,53) = 1.093, p = .301) or block (F (2,106) = .651, p = .524).

In addition, there were no significant interactions between task and condition (F (2,106) = .363, p = .696), task and block (F (4,212) = .481, p = .750), condition and block (F (2,106) = .673, p = .512), or task, condition and block (F (4,212) = .335, p = .854). Mean values for each CST mechanism for the experimenter-led and computer-paced versions of each CST across the three blocks can be found in Appendix I.

Based on this analysis, it can be concluded confidently that the calculation of performance indices across the three tasks in each administration condition was consistent and was therefore used as a measure of ability for processing time, recall time and processing accuracy.

5.5.3 The impact of time constraints on the mechanisms of CSTs

The first research question was to identify the interrelationships between each mechanism (i.e. storage, processing time, recall time, processing accuracy) in each CST and compare these relationships in the computer-paced condition and the experimenter-led condition. Paired t-tests were conducted to identify any significant differences in performance on each CST mechanism in the two administration conditions. Mean scores and t-test statistics for each CST mechanism are given in Table 5.1. There were some significant performance differences. Referring to Table 5.1, processing and recall times were significantly faster in the

[3] This finding was not significant, as α level was set at p <.01 for the study in this chapter.

computer-paced condition compared to the experimenter-led condition for all CSTs. Also, processing accuracy was significantly lower in the computer-paced condition compared to the experimenter-led condition for all CSTs.

Table 5.1 *t-test statistics comparing mean scores for processing time, recall time and processing accuracy in each administration condition for each CST.*

	Processing time *(sd)*	Recall time *(sd)*	Processing accuracy *(sd)*
Counting span EL	2846.40 *(789.65)*	1305.21 *(433.20)*	.99 *(.20)*
Counting Span CP	1856.52 *(545.47)*	1073.18 *(402.34)*	.89 *(.10)*
(df) t	*(89)* 15.22***	*(89)* 5.40***	*(89)* 9.63***
Listening span EL	5062.25 *(585.72)*	10133.57 *(2942.75)*	.96 *(.04)*
Listening span CP	4486.08 *(409.22)*	7454.71 *(2602.08)*	.94 *(.04)*
(df) t	*(85)* 10.24***	*(88)* 8.06***	3.26**
Odd One Out span EL	2800.26 *(480.10)*	3618.69 *(948.92)*	.98 *(.04)*
Odd One Out span CP	1975.05 *(361.84)*	2773.18 *(667.50)*	.94 *(.06)*
(df) t	*(90)* 15.67***	*(90)* 8.40***	*(90)* 6.28***

EL = experimenter-led; CP = computer-paced

**p < .01, ***p < .001

5.5.4 The relationships between the underlying mechanisms of each CST

To identify whether the relationships between the underlying mechanisms of each CST differed across administration conditions, correlations were carried out between these measures within the two administration conditions.

5.5.4.1 Counting Span

Correlations between the CST mechanisms for the experimenter-led version of Counting Span are shown in Table 5.2. Correlations between the CST mechanisms for the computer-paced version of Counting Span are shown Table 5.3. All significant findings are in bold type and indicated by asterisks. Storage was significantly related to processing time, recall time, and processing accuracy. These correlations indicate that higher performance on storage was related to faster processing and recall times and higher accuracy scores. Also in the experimenter-led condition, processing times related to recall times and processing accuracy, indicating that faster processing times were associated with faster recall times and higher accuracy scores. Recall time and processing accuracy were not related in this condition.

Table 5.2 *Correlations between CST mechanisms for Counting Span: Experimenter-led condition.*

	1	2	3	4
1. TTC	-			
2. Processing time	**-.645****	-		
3. Recall time	**-.446****	**.553****	-	
4. Processing accuracy	**.399****	**-.315****	-.053	-

TTC = total trials correct

** p < .01

Correlations between the CST mechanisms for the computer-paced version of Counting Span are shown Table 5.3. All significant findings are in bold type and indicated by asterisks. Storage was significantly related to processing time, recall time, and processing accuracy. These relationships indicate that higher performance on storage was related to faster processing, faster recall times, and higher accuracy scores. Also in the computer-paced condition, processing times related to recall times, indicating that faster processing times were associated with shorter recall times. However, contrary to the relationships in the experimenter-led condition, processing time was not significantly related to processing accuracy. The lack of a relationship between processing time and processing accuracy in the computer-paced condition indicate that, unlike the experimenter-led condition, faster processing was not associated with higher accuracy scores. Recall time and processing accuracy were correlated in the computer-paced condition, showing that faster recall times were linked to higher accuracy scores.

Table 5.3 *Correlations between CST mechanisms for Counting Span: Computer-paced condition*

	1	2	3	4
1. TTC	-			
2. Processing time	**-.498****	-		
3. Recall time	**-.586****	**.564****	-	
4. Processing accuracy	**.314****	.210	**-.315****	-

TTC = total trials correct

** p < .01

5.5.4.2 Listening Span

All correlations are shown in Table 5.4 (experimenter-led) and Table 5.5 (computer-paced) with significant findings in bold type and indicated by asterisks. There were no significant correlations between any of the CST mechanisms for Listening Span in the experimenter-led condition. In the computer-paced condition, storage demonstrated a significant correlation with recall time. This showed that those with higher scores on storage tended to show faster recall times. In addition there was a correlation between processing time and recall time in the computer-paced condition, indicating that faster processing times were related to faster recall times.

Table 5.4 *Correlations between CST mechanisms for Listening Span: Experimenter-led condition*

	1	2	3	4
1. TTC	-			
2. Processing time	-.135	-		
3. Recall time	.125	.149	-	
4. Processing accuracy	.168	.096	-.024	-

TTC = total trials correct

** p < .01

Table 5.5 *Correlations between CST mechanisms for Listening Span. Computer-paced condition*

	1	2	3	4
5. TTC	-			
6. Processing time	-.183	-		
7. Recall time	**-.328****	**.284****	-	
8. Processing accuracy	.216	-.124	-.056	-

TTC = total trials correct

** $p < .01$

5.5.4.3 Odd one out span

All correlations are shown in Table 5.6 (experimenter-led) and Table 5.7 (computer-paced). Significant findings are in bold type and indicated by asterisks. Storage showed significant correlations with processing times and processing accuracy in the experimenter-led condition. This meant that higher storage scores were associated with faster processing times and higher accuracy scores. Also, processing time and recall time were related, indicating that faster processing times were related to faster recall times.

Table 5.6 *Correlations between CST mechanisms for Odd One out Span.*

	1	2	3	4
1. TTC	-			
2. Processing time	**-.408****	-		
3. Recall time	-.187	**.502****	-	
4. Processing accuracy	**.401****	-.263	.039	-

TTC = total trials correct

** $p < .01$

In the computer-paced task, a significant correlation was found between storage scores, processing time and recall time. This showed that higher storage scores were related to faster processing times and faster recall times. Also, faster processing times were related to faster recall times.

Table 5.7 *Correlations between CST mechanisms for Odd One out Span.*

	1	2	3	4
5. TTC	-			
6. Processing time	**-.301****	-		
7. Recall time	**-.305****	**.314****	-	
8. Processing accuracy	.275	.187	.024	-

TTC = total trials correct

** p < .01

5.5.5 Correlations between counterpart CST mechanisms across conditions

Storage, processing time and recall time in the experimenter-led condition were related to their counterpart measures in the computer-paced condition for all tasks. These correlations demonstrate that higher performance on storage in the experimenter-led condition was related to higher storage performance in the computer-paced condition. Also, faster processing times in the experimenter-led condition were related to faster processing times in the computer-paced condition. Further, faster recall times in the experimenter-led condition were related to faster recall times in the computer-paced condition. However, processing accuracy scores in the experimenter-led condition were not related to processing accuracy scores in the computer-paced condition for any of the CSTs. Correlations are shown in Table 5.8

Table 5.8 *Correlations for each CST mechanisms between administration conditions*

	Counting Span	Listening Span	Odd One Out Span
TTC	**.526****	**.613****	**.585****
Processing time	**.640****	**.483****	**.323****
Recall time	**.516****	**.376****	**.352****
Processing accuracy	-.060	.172	.110

TTC = total trials correct

** p < .01

5.5.6 Comparison of correlations between CST mechanisms across conditions

A comparison of independent *r*s was conducted to identify any significant differences in correlations among CST mechanisms in the two conditions (i.e. experimenter-led and computer-paced tasks). Test statistics on the independent *r*s for these correlations can be seen in Table 5.9. The correlation between processing time and processing accuracy was significantly higher in the computer-paced condition compared to the experimenter-led condition for Counting Span. The correlation between storage and recall time was significantly higher in the computer-paced condition compared to the experimenter-led condition for Listening Span. There were no other significant differences. Significant results are shown in bold.

Table 5.9 *Comparison of independent rs between experimenter-led and computer-paced CSTs.*

	Counting	Listening	Odd one out
Storage - processing time	*Z = 1.57, p = .11*	*Z = -0.33, p = .74*	*Z = -.89, p = .37*
Storage - recall time	*Z = 1.28, p = .10*	***Z = 3.11, p < .01***	*Z = 1.24, p = .22*
Storage - processing accuracy	*Z = 0.65, p = .52*	*Z = -0.33, p = .74*	*Z = 1.23, p = .22*
Processing time - recall time	*Z = -0.11, p = .91*	*Z = -0.95, p = .34*	*Z = 1.48, p = .14*
Processing time - processing accuracy	***Z = -3.6, p < .001***	*Z = 1.47, p = .14*	*Z = -.37, p = .71*
Recall time - processing accuracy	*Z = 1.82, p = .06*	*Z = 0.21, p = .83*	*Z = 0.87, p = .38*

5.5.7 Multidimensional scaling

As differences in the interrelationships between the CST mechanisms were observed in the computer-paced compared to the experimenter-led condition for some tasks (see section 5.4.4), it was important to identify any underlying principal relationships between processing time, recall time, processing accuracy, and storage that were dependent on administration condition. Multidimensional scaling (MDS) was chosen to examine the principal relationships between the CST mechanisms when measured in the experimenter-led and computer-paced conditions. MDS can model nonlinear relationships among dissimilar measurements (e.g. time or accuracy scores) (Jaworski, & Chupetlovska-Anastasova, 2009). Items plotted close together in an MDS model are assumed to share similarities (i.e. reflecting similar abilities), and those that appear further apart are assumed to be dissimilar (i.e. reflecting different abilities). If recall time, processing speed, processing accuracy, and storage reflect four separable abilities, then these differences should be evident in their representation (i.e. distance from each other) in the model. If the abilities related to these constructs are similar, this should be evident by their proximity in the models. For each CST, correlations were calculated between each mechanism (i.e. storage; recall time; processing time; processing accuracy). These were then used as distances in the scale analyses.

5.5.7.1 Counting Span

When all four mechanisms of the Counting Span task were entered into the MDS model, a final S-stress value of .048, after three iterations, indicated good dissimilarity. The model accounted for 99.6% variance in the dissimilarity matrix. The final model is shown in Figure 5.1.

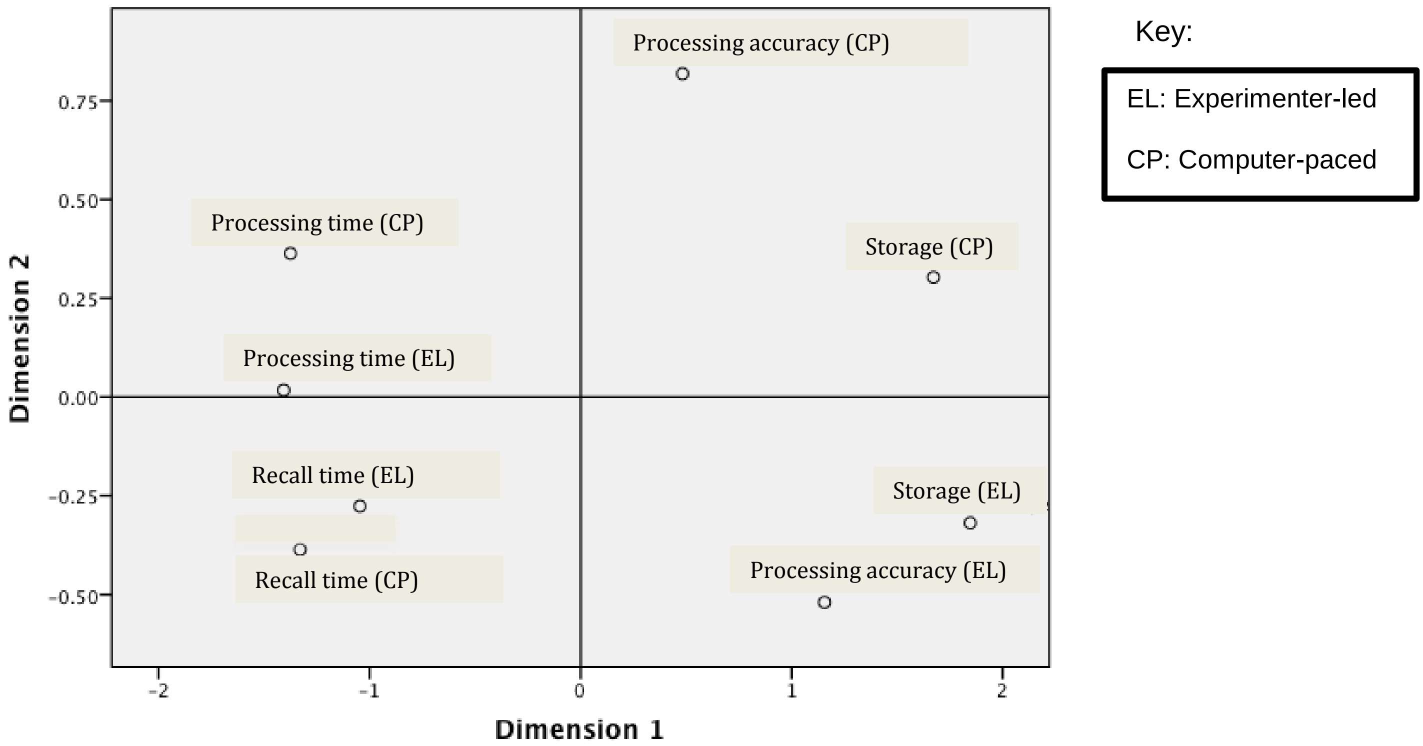


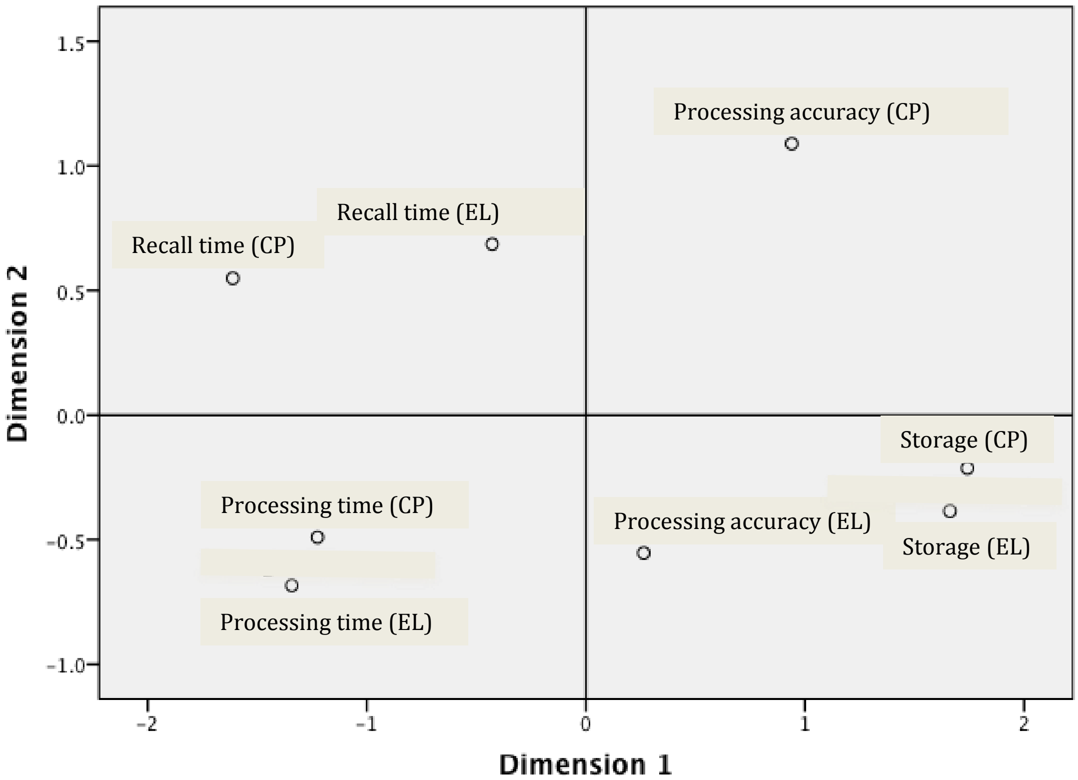
Figure 5.1. MDS model showing dimensions for CST mechanisms for Counting Span

The MDS analysis produced a model whereby processing time and recall time from both administration conditions were plotted on the left-hand side in Dimension 1, and storage and processing accuracy from both administration conditions were plotted on the right-hand side in Dimension 1. This demonstrated an overall difference in ability between time (i.e. processing time, recall time) and accuracy (i.e. storage, processing accuracy), regardless of whether this was related to the experimenter-led or computer-paced condition.

For Dimension 2, MDS placed recall time, processing accuracy and storage in the experimenter-led condition below the median line, and processing time, processing accuracy and storage in the computer-paced condition were placed above the median line. Whilst accepting that processing time in the experimenter-led condition was neutral (i.e. at the mid point in Dimension 2), and that recall times for both conditions appeared to reflect a very similar ability (i.e. situated close together in the model), the second dimension showed a difference in processing accuracy and storage (and to a degree processing time) scores dependent on whether or not they were related to the experimenter-led or the computer-paced condition.

5.5.7.2 Listening Span

When all four mechanisms of the Listening Span task were entered into the MDS model, a final S-stress value of .116, after four iterations, indicated moderate dissimilarity. The model accounted for 95% variance in the dissimilarity matrix. The final model is shown in figure 5.2.



Key:

EL: Experimenter-led

CP: Computer-paced

Figure 5.2: MDS model showing dimensions for CST mechanisms for Listening Span

For Listening Span, MDS produced a model that placed recall time and processing time to the left in Dimension 1 and storage and processing accuracy were placed to the right in Dimension 1. This showed an overall difference in ability between time (i.e. recall time and processing time) and accuracy (i.e. processing accuracy and storage) regardless of administration condition. For Dimension 2, MDS placed processing time and storage (in both administration conditions) below the median line, and recall time (in both administration conditions), above the median line. This demonstrated that storage and processing time in both conditions were a separate ability from recall time (also in both conditions). However, processing accuracy in the computer-paced condition was plotted above the median line and processing accuracy in the experimenter-led condition was plotted below the median line. Therefore, ability with regard to processing accuracy was separated depending on administration condition. It is noted that a degree of similarity was shown for both storage scores, and also for both processing time scores, as they were both situated in close proximity to their counterpart in the model.

5.5.7.3 Odd One Out Span

When all four mechanisms of the Odd One Out Span task were entered into the MDS model, a final S-stress value of .067, after four iterations, indicated good dissimilarity. The model accounted for 97% variance in the dissimilarity matrix. The final model is shown in figure 5.3.

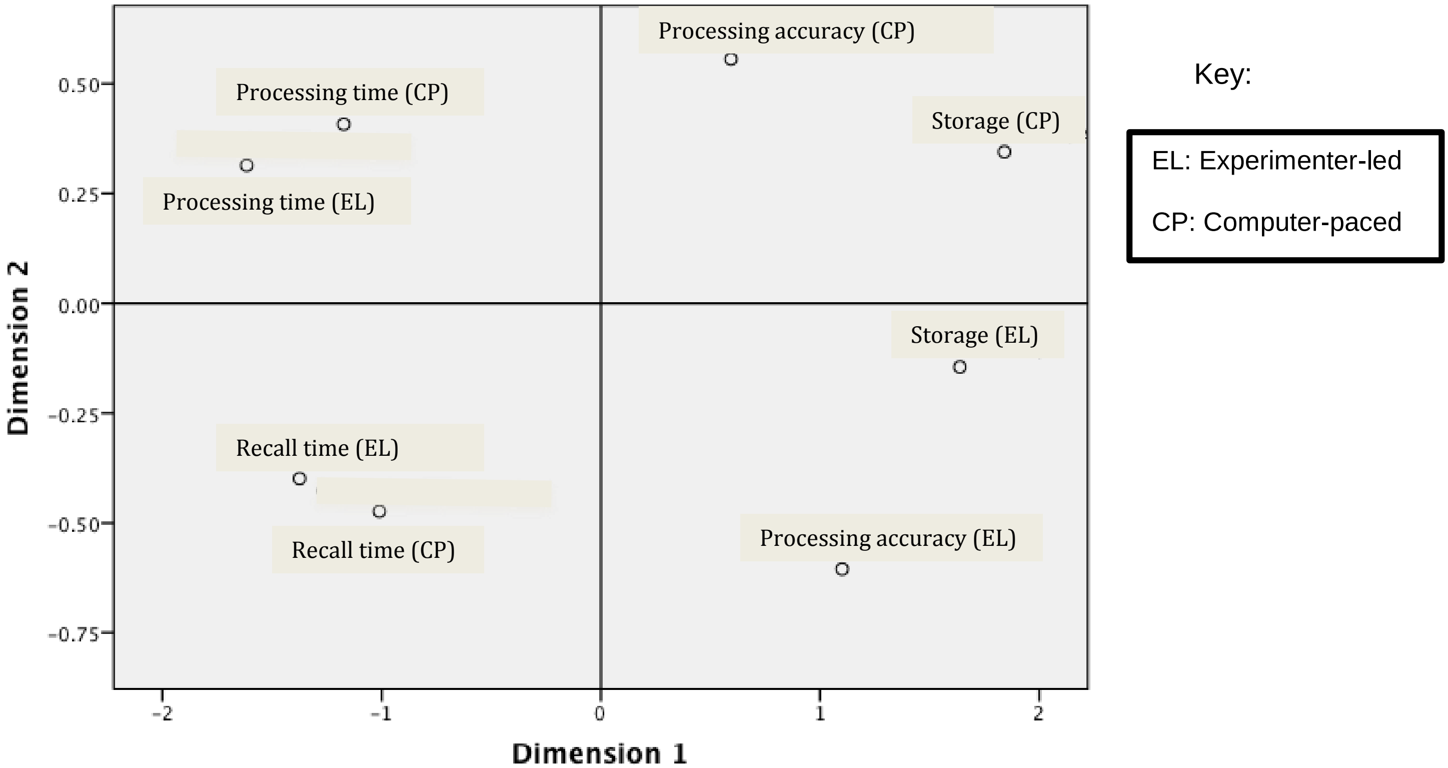


Figure 5.3: MDS model showing dimensions for CST mechanisms for Odd One Out Span.

For Odd One Out Span, MDS produced a model that placed recall time and processing time to the left in Dimension 1 and storage and processing accuracy were placed to the right in Dimension 1. This showed an overall difference in ability between time (i.e. recall time and processing time) and accuracy (i.e. processing accuracy and storage) regardless of administration condition. For Dimension 2, MDS placed processing time (in both conditions) above the median line and recall time below the median line (in both conditions). This showed that processing time and recall time were separate abilities, regardless of administration condition. However, processing accuracy and storage in the computer-paced condition were placed above the median line and processing accuracy and storage in the experimenter-led condition were placed below the median line. This showed that storage and processing accuracy are more similar in terms of ability when relating to the same administration condition.

5.5.8 The underlying relationships between CST mechanisms and administration condition

To further understand the relationships between the four mechanisms of the CSTs and the impact of task condition, MDS analysis was conducted in the previous sections using the *r*-values from the correlation analysis for each relationship within each CST. The key questions addressed by this analysis were: What are the relationships between the four underlying abilities? Do the four underlying mechanisms of the CSTs represent similar or different abilities? Were any apparent similarities or differences dependent on whether or not the tasks were time-constrained?

For Counting Span, abilities relating to processing accuracy, processing time and storage in the experimenter-led condition were dissimilar to the equivalent abilities in the computer-paced task. This suggested that performance on these task mechanisms was not a stable ability regardless of administration condition, but one that was affected by time constraints. Yet recall timing appeared to be more consistent across administration conditions, in that this ability in the experimenter-led condition was similar to the same ability in the computer-paced condition. Furthermore abilities represented by processing time and recall time in both administration conditions were dissimilar to abilities represented by processing accuracy and storage. This suggested that the abilities measured in terms of speed (i.e. processing time, recall time) were dissimilar from those measured in terms of accuracy (i.e. processing accuracy and storage).

For Listening Span, the ability relating to processing accuracy in the experimenter-led condition was dissimilar to the equivalent ability in the computer-paced condition, whereas processing time and storage in the experimenter-led condition were similar to their counterparts in the computer-paced condition. The ability relating to recall time did not appear to be strongly separated or grouped by administration condition. This indicated that ability related to processing accuracy was affected by time-constraints; yet processing time and storage were less affected. However, similar to Counting Span, abilities represented by processing time and recall time were dissimilar to abilities represented by processing accuracy and storage. This, again, suggested that the abilities that were measured in terms of speed were separate from those measured in terms of accuracy.

For Odd One Out Span, processing time in the experimenter-led condition was shown to be similar to the same ability in the computer-paced condition. The same was the case for recall time. Conversely, processing accuracy and storage in the experimenter condition were dissimilar to their counterparts in the computer-paced condition. Consistent with Counting and Listening Span, for Odd One Out Span, abilities represented by processing time and recall time were dissimilar to abilities represented by processing accuracy and storage. This further supported the finding that the abilities measured in terms of speed were separate from those measured in terms of accuracy.

Having briefly discussed the interrelationships between the mechanisms of CSTs and how they were affected by administration condition, the following section addresses how each mechanism accounted for variance in the various measures of HLC, and how such predictive relationships were affected by time restrictions placed on processing durations.

5.6 The relationship between HLC and the mechanisms of CSTs

To examine the relationships between HLC and each CST mechanism in each task and condition, correlational analysis was conducted. These calculations were performed for all CSTs and are reported in the following sections.

5.6.1 Counting Span

All correlations are shown in Table 5.10, with significant findings in bold type and indicated by asterisks. As reported in Chapter Four, higher span scores (i.e. storage) in the experimenter-led task were related to better performance in non-verbal reasoning and mathematics. Higher span scores (i.e. storage) in the computer-paced task were related to better performance in non-verbal reasoning, reading and mathematics. Processing time in the experimenter-led condition was related to mathematics ability only, with faster processing times related to higher maths scores. In the computer-paced condition, processing time was related to all HLC measures, namely faster processing was associated with higher ability in non-verbal reasoning, reading, and mathematics. Recall time was significantly related to mathematics in both conditions, such that faster recall times related to higher maths scores. Processing accuracy did not correlate significantly with any HLC measures.

Table 5.10 *Correlations between CST mechanisms and HLC measures for Counting Span.*

	Experimenter-led				Computer-paced			
	Storage	Processing time	Recall time	Processing accuracy	Storage	Processing time	Recall time	Processing accuracy
1. Non-verbal reasoning	**.437****	-.213	-.155	.047	**.345****	**-.384****	-.018	-.140
2. Reading	.265	-.199	-.173	-.193	**.275****	**-.329****	-.054	-.028
3. Maths	**.613****	**-.546****	**-.290****	.228	**.545****	**-.619****	**-.341****	.046

** $p < .01$

5.6.2 Listening Span

All correlations are shown in Table 5.11. Significant findings are in bold type and indicated by asterisks. In the experimenter-led condition there were correlations between storage and mathematics, such that higher span scores were related to higher maths scores. In addition, greater processing accuracy correlated with higher maths scores and better performance on the non-verbal reasoning task. However, there were no significant correlations with HLC for either processing time or recall time in the experimenter-led condition. Storage in the computer-paced version of the Listening Span task showed significant correlations with reading and mathematics: higher span scores were related to higher scores on tests of reading and mathematics. Recall time was related to maths scores in this condition, with faster recall times being associated with higher maths scores.

Table 5.11 *Correlations between CST mechanisms and HLC measures for Listening Span.*

	Experimenter-led				Computer-paced			
	Storage	Processing time	Recall time	Processing accuracy	Storage	Processing time	Recall time	Processing accuracy
1. Non-verbal reasoning	.193	.051	.116	**.277******	.263	.049	-.050	.049
2. Reading	.246	.062	-.012	-.029	**.299****	-.046	-.253	-.049
3. Maths	**.301****	-.172	-.150	**.275****	**.432****	-.197	**-.271****	.184

** $p < .01$

5.6.3 Odd One out Span

All correlations are shown in Table 5.12. Significant findings are in bold type and indicated by asterisks. Three significant correlations were observed between CST mechanisms and HLC for the Odd One Out Span task; all of which were apparent in the computer-paced condition. Storage was related to mathematics ability, with higher span scores correlated to higher maths scores. Also in the computer-paced condition, faster processing times related to higher scores on tests of non-verbal reasoning and mathematics.

Table 5.12 *Correlations between CST mechanisms and HLC for Odd One Out Span.*

	Experimenter-led				Computer-paced			
	Storage	Processing time	Recall time	Processing accuracy	Storage	Processing time	Recall time	Processing accuracy
1. Non-verbal reasoning	.149	-.050	.011	.243	.254	**-.274****	-.031	-.103
2. Reading	.067	-.066	-.106	.137	.149	-.159	-.069	-.123
3. Maths	.236	-.177	-.129	.182	**.453****	**-.399****	-.042	.010

** *p* < .01

5.7 Comparison of CST mechanism correlations between administration conditions

A comparison of dependent *r*s was conducted to identify any significant differences in correlations between each CST mechanism and the measures of HLC in the two conditions of experimenter-led and computer-paced tasks. However, no significant differences were identified. Test statistics on the dependent *r*s for these correlations can be seen in Table 5.13.

Table 5.13 *Comparison of dependent rs between mechanisms for experimenter-led and computer-paced CSTs.*

CST mechanisms	Counting	Listening	Odd one out
Storage – NVR	$Z_H = 0.08$, $p = .21$	$Z_H = -0.26$, $p = .40$	$Z_H = -0.36$, $p = .36$
Storage - Reading	$Z_H = -0.21$, $p = .42$	$Z_H = -0.35$, $p = .36$	$Z_H = 0.14$, $p = .44$
Storage - Maths	$Z_H = 0.23$, $p = .41$	$Z_H = -0.78$, $p = .22$	$Z_H = 0{,}42$, $p = .34$
Processing time - NVR	$Z_H = 2.02$, $p = .04$	$Z_H = 0.02$, $p = .99$	$Z_H = 1.85$, $p = .06$
Processing time - Reading	$Z_H = 1.51$, $p = .13$	$Z_H = 1.00$, $p = .32$	$Z_H = 0.76$, $p = .45$
Processing time - Maths	$Z_H = 1.05$, $p = .29$	$Z_H = 0.24$, $p = .81$	$Z_H = 1.91$, $p = .06$
Recall time - NVR	$Z_H = 0.24$, $p = .81$	$Z_H = 1.41$, $p = .16$	$Z_H = 0.35$, $p = .73$
Recall time - Reading	$Z_H = -1.15$, $p = .25$	$Z_H = 2.07$, $p = .04$	$Z_H = -0.31$, $p = .76$
Recall time - Maths	$Z_H = 0.52$, $p = .60$	$Z_H = 1.05$, $p = .29$	$Z_H = -0.72$, $p = .47$
Processing accuracy - NVR	$Z_H = 1.22$, $p = .22$	$Z_H = 1.71$, $p = .09$	$Z_H = 2.47$, $p = .02$
Processing accuracy - Reading	$Z_H = -1.08$, $p = .28$	$Z_H = 0.15$, $p = .88$	$Z_H = 1.84$, $p = .07$
Processing accuracy – Maths	$Z_H = 1.20$, $p = .23$	$Z_H = 0.69$, $p = .49$	$Z_H = 1.22$, $p = .22$

NVR = Non-verbal reasoning

Comparisons are significant at the *p*. < .01 level[4]

[4] The α level was set at $p < .01$ for the study in this chapter.

5.8 The contribution of CST mechanisms to HLC

In Chapter Four, it was demonstrated that time restrictions on the processing component of the CSTs changed the way in which they were related to measures of HLC. The previous sections have shown that the correlational relationships between each CST mechanism and HLC were not significantly different in the computer-paced tasks compared to the experimenter-led tasks. However, the hypothesis in this chapter was that each underlying mechanism of CSTs (i.e. storage, processing time, recall time, processing accuracy) might account for different portions of variance in non-verbal reasoning, reading and mathematics.

To identify whether the inclusion of processing time, recall time and processing accuracy in the regression models would account for variance in the three areas of HLC, beyond that accounted for by storage alone (i.e. as indicated in Chapter Four), hierarchical regression was conducted. For each CST in each administration condition, storage was entered at Step 1 of the model to control for its contribution to variance in HLC. Then, as there were no justifications to assume any one of the remaining CST mechanisms would be more important in predicting HLC than another, processing time, recall time and processing accuracy were all entered together at Step 2. Statistical checks for each regression (Durbin-Watson, tolerance/VIF statistics, Cook's/Mahalanobis distances, plots of standardised residuals/predicted standardised values, standardised residuals, partial plots) did not indicate multicollinearity or cases with undue influence. As such, all cases were included in the final analysis (Field, 2009).

5.8.1 Non-verbal reasoning

The information in Table 5.14 includes total variance accounted for in non-verbal reasoning (total R^2) and standardised β-values. Data are only included for those models where total variance accounted for in non-verbal reasoning was significant. It was found that the additional CST mechanisms contributed to the predictive power of the regression in some instances. Therefore, individual significant **β** values are provided in italics beneath Step 2. All significant values are in bold and indicated by asterisks where relevant.

Table 5.14 *Summary of hierarchical regressions for CST mechanisms predicting non-verbal reasoning.*

Predictor variable		**Total R^2**	**Change in R^2**	**β**	***F* Change**
Counting					
EL	Step 1:	**.19****	**.18*****	**.43*****	**20.82*****
	Step 2:		.01		0.24
CP	Step 1:	**.30*****	**.12****	**.35****	**12.02****
	Step 2:		**.18*****		**7.48*****
Processing time				***-.43*****	
Recall time				***.45*****	

EL = experimenter-led, CP = computer-paced

Step 1: storage (i.e. TTC), Step 2: processing time, recall time, processing accuracy

** p<.01; ***p<.001

For Counting Span, after controlling for storage in the computer-paced condition, processing time (β =-.43, p < .01) and recall time (β = .45, p < .01) accounted for further variance in non-verbal reasoning (change in R^2 = .18, p < .001). The experimenter-led version of Counting Span, and both versions of Listening Span and Odd One Out Span did not account for significant portions of variance in non-verbal reasoning at Step 2 (i.e. when the additional CST mechanisms were entered into the model).

5.8.2 Reading

The information in Table 5.15 includes total variance accounted for in reading (total R^2) and standardised β-values. Data are only included for those models where total variance accounted for in reading was significant. It was found that the additional CST mechanisms contributed to the predictive power of the regression in some instances. Therefore, individual significant **β** values are provided in italics beneath Step 2. All significant values are in bold and indicated by asterisks where relevant.

Table 5.15 *Summary of hierarchical regressions for CST mechanisms predicting reading.*

Predictor variable		Total R^2	Change in R^2	β	F Change
Counting					
EL	Step 1:	**.15****	.07	.26	6.40
	Step 2:		.08*		2.79
Processing accuracy				***-.30****	
CP	Step 1:	**.19****	**.08****	**.28****	**7.25****
	Step 2:		.11		3.92

EL = experimenter-led, CP = computer-paced

Step 1: storage (i.e. TTC), Step 2: processing time, recall time, processing accuracy

** p<.01; ***p<.001

Only Counting Span, in both the experimenter-led (R^2 = .15, p < .01) and computer-paced change in R^2 = .19, p < .01) conditions, accounted for variance in reading ability when all four CST mechanisms were entered into the model. The experimenter-led version accounted for further variance in reading ability at Step 2 (change in R^2 = .08*, p < .01). Although the analysis in this study has an **α** value set at .01 (cf. section 5.4), the R^2 at Step 2 is stated here due to the finding of a significant **β** value for processing accuracy (β =-.30, p < .01), also at Step 2.

However, adhering to the self-applied rule of **α** = .01, Counting, Listening Span and Odd One Out Span did not account for significant portions of variance in reading ability at Step 2 (i.e. after controlling for storage), regardless of administration condition.

5.8.3 Mathematics

The information in Table 5.16 includes total variance accounted for in mathematics (total R^2) and standardised β-values. Data are only included for those models where total variance accounted for in mathematics was significant. It was found that the additional CST mechanisms contributed to the predictive power of the regression in some instances. Therefore, individual significant **β** values are provided in italics beneath Step 2. All significant values are in bold and indicated by asterisks where relevant.

Table 5.16 *Summary of hierarchical regressions for CST mechanisms predicting mathematics.*

Predictor variable		Total R^2	Change in R^2	β	*F* Change
Counting					
EL	Step 1:	**.42*** **	**.36*** **	**.60*** **	**49.20*** **
	Step 2:		.06		2.84
CP	Step 1:	**.49*** **	**.30*** **	**.55*** **	**37.55*** **
	Step 2:		**.20*** **		**10.97*** **
	Processing time			***-.63****	
Listening					
CP	Step 1:	**.15** **	**.10** **	**.32** **	**10.02** **
	Step 2:		.04		1.42
Odd one out					
CP	Step 1:	**.34*** **	**.21*** **	**.46*** **	**20.53*** **
	Step 2:		**.12** **		**4.47** **
	Processing time			***-.30****	

EL = experimenter-led, CP = computer-paced

Step 1: storage (i.e. TTC), Step 2: processing time, recall time, processing accuracy

** p<.01; ***p<.001

In the computer-paced version of Counting Span, when storage was controlled for in Step 1, processing time (β = -.63, p < .001) accounted for further variance in mathematics ability. With regard to the computer-paced version of Odd One Out Span, after controlling for storage in Step 1, processing time (β = -.30, p < .01) accounted for further variance. The experimenter-led version of Counting and Odd One Out Span, and both versions of Listening Span did not account for significant portions of further variance in mathematics ability at Step 2 (i.e. after controlling for storage).

5.9 Discussion

There were two main aims of the current study. The first was to examine the relationship between the underlying mechanisms of CSTs in a computer-paced administration condition compared to an experimenter-led condition. Then, the relationships between these underlying mechanisms and HLC were investigated to understand why CSTs related to HLC differently depending on administration condition. Therefore, the relationships between storage, processing time, recall time, and processing accuracy were examined along with three measures of HLC (i.e. non-verbal reasoning, reading, mathematics).

5.9.1 The effect of time restrictions on CST mechanisms

There were three predictions for the first research question in this study; each of which are addressed here.

5.9.1.1 The relationship between processing time and storage

For Counting and Odd One Out Span, it was found that faster processing times were associated with increased storage. This finding was evident in both administration conditions and supports both the resource-sharing (Case et al., 1982; Daneman & Carpenter, 1980) and the task-switching hypotheses (Towse & Hitch, 1995; Towse et al., 1998; Towse et al., 2002), which argue that faster processing equates to increased storage capacity due to reduced processing resource requirements (in the former case of resource-sharing) and reduced memory decay (in the latter case of task-switching). Barrouillet et al. (2004, exp. 4) also demonstrated a linear relationship between processing speed and storage in adults (i.e. faster processing equated to higher span scores). This was interpreted as evidence for the presence of an attentional refreshing mechanism that enabled participants with faster processing speeds to utilise gaps within the processing task to switch attention back to memory items in order to refresh them. This has been also observed in children from approximately the age of seven years (Barrouillet & Camos, 2001; Camos & Barrouillet, 2011).

However, in the current study, this relationship between processing times and storage was evident in both administration conditions, which contradicts previous research that has found that when participants are able to control how much time is allocated to processing, slower processing times were linked to higher span scores (Friedman & Miyake, 2004; St. Clair- Thompson, 2007). Such studies have interpreted this finding as evidence of participants delaying processing in order to focus on maintenance strategies, which in turn increased storage.

The finding in the current study that the processing time-storage relationship was not altered by whether or not the CSTs were time-constrained may be due to the use of experimenter-led, as opposed to participant-led CSTs to assess WM performance in an administration condition that was not time constrained. Friedman & Miyake (2004) and St Clair-Thompson (2007) both used participant-led tasks in their studies with adults. However, in order to reduce the likelihood of longer processing times in children due to distraction (i.e. rather than maintenance strategy use) the current study used experimenter-led tasks. This methodology still allowed participants to delay processing during stimuli presentation in order to maintain items in memory; however it meant that the onset of subsequent stimuli (or recall prompt, as would be the case at the end of a trial) after processing was not controlled by the participant and could not therefore be delayed. A comparison of processing times between administration conditions found that processing times were significantly longer in the experimenter-led condition for all WM tasks; however, this did not equate to higher storage scores. This may indicate that, in order for maintenance strategies to be effective in increasing storage, they need to occur after presentation of the to-be-remembered item (i.e. equal to the output of the processing stimuli in the case of the CSTs in this study), and before the presentation of the next processing item as would be possible in participant-led CSTs but not experimenter-led CSTs.

This is consistent with the findings from a recent study (Bayliss, Bogdanovs & Jarrold, 2015) that found maintenance opportunity (i.e. an unfilled delay interval) after the presentation of memoranda and before processing resulted in better recall in working memory, compared to when a delay interval was presented after processing.

It is necessary to ask why the storage-processing time relationship was not observed for Listening Span regardless of administration condition. This may be due to the way in which the stimuli were presented in the Listening Span task. For the Counting and Odd One Out Span tasks, the stimuli were presented on screen concurrently allowing the participant to process items while they were visually available. However, for the Listening Span task, the sentences were presented aurally and so the participant may not have begun to process the stimulus until its presentation was complete. After that time, it was no longer available. Although the recording of processing durations did not commence until the sentence was complete, the fact that the stimulus was not present during processing may have caused additional delay, thereby cancelling out any effect of processing speed.

5.9.1.2 The effect of time constraints on processing accuracy between CST mechanisms across conditions

It was predicted that time restrictions would have a greater effect on processing accuracy in the verbal task, compared to accuracy in the visuospatial and numerical tasks. However, this was not the case. In fact, the difference in mean processing accuracy scores between the two versions of the verbal task ($p < .01$) was not as significant as it was for the visuospatial (p, $< .001$) and numerical ($p < .001$) tasks. This does not support the prediction that complexity of processing stimuli is domain-specific, as processing accuracy was similarly affected across the tasks.

However, in the Counting, Listening and Odd One Out Span tasks, correlations were found between comparable skills for storage, processing time and recall time across the two conditions (i.e. experimenter-led and computer-paced).

However, this was not the case for processing accuracy. This may indicate that time constraints placed on the processing component of CSTs affected processing accuracy at an individual level, with some children forfeiting processing accuracy in the computer-paced tasks compared to the experimenter-led tasks, whilst other children did not. Furthermore, as processing time was significantly related between administration conditions but processing accuracy was not, this supports research that has reported findings suggesting a separation of processing time and processing accuracy within WM (Unsworth et al, 2009; Waters & Caplan, 1996). This point is addressed in greater detail in Section 5.9.3.

5.9.1.3 The relationship between processing time and processing accuracy

Results showed that, in the Counting Span task, faster processing was related to fewer processing errors in the experimenter-led condition, but not in the computer-paced condition. Therefore participants who processed information more quickly were also more accurate, but not when time was restricted. Whereas previous theories of WM have proposed that processing time and accuracy are a single entity indicative of processing efficiency (Daneman & Tardif, 1987), the results from the current study suggests that, for Counting Span at least, they are different mechanisms holding separate relationships with each other. However, relationships between processing time and accuracy were not observed in the Listening or Odd One Out Span tasks. Consistent with findings in Chapter Four, this demonstrates that the effect of time constraints on CSTs differs dependent on task type (i.e. Counting, Listening or Odd One Out Span).

5.9.1.4 A discussion of additional findings: The effect of time restrictions on CST mechanisms

Although relationships between other CST mechanisms within each administration condition were included in the predictions for this chapter, this section includes a brief discussion of any findings in the interest of a comprehensive understanding of the effect of time constraints on CSTs. First, it is noted that recall durations for the Listening Span task were considerably longer compared to the Counting and Odd One Out Span tasks. This was consistent with findings from previous studies (e.g. Cowan et al., 2003) that have found that when it is possible to use semantic cues to recall memoranda, recall times are longer. Second, in the Counting Span task, the quicker the participant could recall the memory items (i.e. recall times), the greater the recall accuracy (i.e. storage). This finding was evident in both administration conditions, which was inconsistent with research that has shown this relationship to be evident only when maintenance is disrupted (Rose et al., 2014). However, the findings in the Odd One Out and Listening Span tasks were in line with the findings of Rose et al., as there was only a relationship between recall time and storage when the tasks were time-constrained. Therefore, whilst the experimenter-led administration condition seemed to result in differences in the relationship between storage and recall times for the Listening and Odd One Out Span tasks, this did not affect the relationship in the Counting Span task.

Higher storage scores were an indication of fewer errors in processing in both conditions for Counting Span. This finding was consistent with previous studies (Daneman & Tardif, 1987; Shah & Miyake, 1996; Unsworth et al, 2009) and contradicted theories that argue that it is the allocation of maintenance strategies at the expense of processing that increases recall (Friedman & Miyake, 2004; St Clair-Thompson, 2007). Faster processing and more accurate processing both correlated with span scores. This may indicate that participants who completed processing more quickly and accurately were able to switch to memory items in order to refresh them, consistent with a task-switching perspective (Towse & Hitch, 1995; Towse et al., 2002), and theories that maintain that a faster processing speed allows for attentional switching between processing items to refresh memoranda (Barrouillet et al., 2004; Barrouillet & Camos, 2001; Camos & Barrouillet, 2011).

For Listening Span, storage did not relate to processing accuracy in either administration condition. The processing stimulus for Listening Span was slightly different than that for Counting and Odd One Out Span in that the accurate output of information (i.e. whether the sentence was true or false) was not identical to the recall item (i.e. the last word of the sentence). Therefore, the participant could more easily forgo processing accuracy, yet still correctly recall the memory items. This may explain why higher span scores were not related to higher processing accuracy scores in either condition of the Listening Span task.

Processing accuracy related to storage in the experimenter-led version of the Odd One Out task, but not in the computer-paced condition. Therefore, accuracy in processing visuospatial stimuli was affected by time constraints, even when these restrictions accounted for individual differences in visual processing speeds. This may be explained by the difficulty that seven- and eight-year-olds children have with maintaining visuospatial information in WM before the age of approximately eight-years and the influence of individual abilities in strategy use (Henry et al., 2012) and attentional capacity (Cowan, 1995) (see Pickering, 2001 for a review). Therefore, when processing time was limited in the computer-paced version of the Odd One Out task, the ability to utilise skills that are only just beginning to emerge in this age group may have been compromised, leading to errors in processing accuracy.

5.9.2 Time restrictions and relationships between CST mechanisms and HLC

The second research question in the current study examined how the underlying mechanisms of the CSTs related to measures of HLC. There were three predictions; each of which is addressed in the following section.

5.9.2.1 The relationship between processing time and HLC

Correlational analysis showed that, for the experimenter-led version of Counting Span, processing time was only related to ***mathematics ability.*** This was inconsistent with the prediction that processing time would be related to all measures of HLC. However, consistent with the second prediction that faster processing times in the computer-paced condition would predict HLC, Counting Span showed links with all measures of HLC and accounted for further variance (i.e. after controlling for storage) in ***non-verbal reasoning*** and ***mathematics*** in this condition. In addition, processing time in Counting Span predicted ***mathematics ability*** in the computer-paced task after controlling for storage. This finding was consistent with previous research that has found processing time to be predictive of HLC in adults (Unsworth et al., 2009) and in children (Bayliss et al., 2003; 2005). However, the current study compared two administration conditions (i.e. experimenter-led and computer-paced) and, therefore, it was possible to demonstrate how the relationship between processing time and its role in predicting HLC changed dependent on administration condition. Furthermore, such findings demonstrate the importance of considering processing speed (Barrouillet & Camos, 2001; Fry & Hale, 1996; Towse & Hitch, 1995) in CSTs when predicting HLC.

Processing time in both versions of the Listening Span task did not relate to any measures of HLC. However, processing time in the computer-paced version of Odd One Out Span was related to ***non-verbal reasoning*** *and* ***mathematics***. Also, in the Odd One Out Span computer-paced condition, processing time accounted for further variance in ***mathematics ability*** over and above contributions from storage. This was again consistent with the prediction that processing time would account for further variance in HLC in the computer-paced condition.

5.9.2.2 The relationship between recall time and HLC

Inconsistent with the prediction that recall time in the Listening Span task would be related to HLC, recall times did not predict non-verbal reasoning, reading or mathematics. However, recall time in Counting Span accounted for further variance in ***non-verbal reasoning*** when controlling for storage in the computer-paced task. Although this was consistent with previous research (Cowan et al., 2003; Towse et al., 2008a; Towse et al., 2008b), it was not evident in the experimenter-led condition of Counting Span or in either version of the Listening and Odd One out Span tasks.

5.9.2.3 A discussion of additional findings: Processing accuracy and HLC

Correlational analysis showed that processing accuracy related to HLC in the experimenter-led version of the Listening Span task; and this relationship was evident for ***non-verbal reasoning*** and ***mathematics*** only. In addition, this mechanism also accounted for further variance in reading (i.e. beyond storage) in the experimenter-led version of Counting Span. Therefore, the relationship between processing accuracy in CSTs and HLC was evident only when times were unrestricted. The reason for this is unclear but may be indicative of a forfeiting of processing accuracy in the computer-paced tasks in order to achieve the main goal of memoranda maintenance.

5.9.3 Summary of findings

Findings from the current chapter supported the prediction that faster processing times would link to higher storage scores indicating an increase in speed to prevent decay. However, the alternative prediction that slower processing times in the experimenter-led task would relate to higher storage scores indicating the use of maintenance strategies to preserve memory items was rejected.

Consistent with predictions regarding the separation of processing accuracy and processing time, the relationship between these two mechanisms changed dependent on administration condition and domain. In addition, the pattern of processing accuracy across the sample was not consistent across administration conditions suggesting individual differences in the effect of time restrictions, with some participants forfeiting processing accuracy whilst others maintained performance levels. However, the expectation that processing accuracy would be differently affected by time-restrictions dependent on complexity of stimuli was not upheld, with decreases in processing accuracy in the computer-paced condition compared to the experimenter-led condition being similar across tasks.

There was an expectation that processing times in the computer-paced tasks would predict non-verbal reasoning and mathematics. This was supported by the findings, indicating the importance of processing speed in HLC. Finally, the prediction that faster recall times in the experimenter-led version of the verbal WM task would relate to HLC (i.e. indicating the importance of retrieval from secondary memory in HLC) was not supported.

5.10 Executive summary

The study in this chapter support the task-switching, resource-sharing hypotheses and TBRS model of WM, as children who processed information more quickly tended to demonstrate a higher storage capacity. However, the multi-component model view that the use of maintenance strategies are important in WM were challenged, as participants were not able to make use of the additional time in the experimenter-led condition to increase their storage capacity. It could be argued that this finding supports unitary theory in that attentional focus, not strategy use, may be the key element in maintaining memoranda. However, it should be considered that whilst storage accounted for variance in HLC in the experimenter-led condition, processing times in the computer-paced tasks accounted for further variance in non-verbal reasoning and mathematics. As stated by St Clair-Thompson (2007, p. 361), placing temporal constraints on CSTs “changed the nature of what the tasks measured”, and the role of processing time may indicate that it is the ability to adjust processing performance in order to preserve storage items that is fundamental in WM, and therefore HLC. This suggests that future studies examining the WM-HLC relationship using CST storage scores alone can benefit from including processing time, recall time and processing accuracy as predictors of HLC.

6 Chapter Six: The role of other executive skills in the relationship between working memory and high-level cognition.

6.1 Chapter Overview

The previous two chapters have demonstrated that imposing time-constraints on complex span tasks affected their relationships with high-level cognition. This chapter built on these findings by examining the relationship between other key executive skills, complex span task performance and high-level cognition. Specifically, the contributions of task-switching and inhibition to non-verbal reasoning, reading and mathematics ability were examined.

6.2 Research Rationale

Investigations in the previous two chapters demonstrated that, with regard to high-level cognition (HLC), the predictive strength of complex span tasks (CSTs) was dependent not only on administration condition (i.e. experimenter-led or computer-paced) but also on task type (i.e. Counting, Listening or Odd One Out Span). Moreover, time constraints on processing affected the underlying CST mechanisms (i.e. processing time, recall time, processing accuracy), which in turn accounted for further variance in HLC beyond that accounted for by storage. This supported the view that considering CST performance beyond measures of storage can contribute to an understanding of the WM-HLC relationship (Bayliss et al., 2003; 2005; Unsworth et al., 2009).

However, there are other executive abilities skills that may play a role in the WM-HLC relationship and, therefore, are important to consider. The abilities that are most commonly investigated in children are updating[5], inhibition and task-switching

[5] As discussed in Chapter One, research has shown that measures of WM and updating assess the same construct (St Clair-Thompson & Gathercole, 2006). As a result, they are considered to be the same construct for the purpose of this thesis.

(e.g. Huizinga et al., 2006; St Clair-Thompson & Gathercole, 2006; van der Sluis et al., 2007; van der Ven et al., 2013). Task-switching describes the ability to change cognitive strategies to achieve a known goal dependent on success (Anderson, 2002). Inhibition is commonly defined as the ability to suppress behaviours which, although potent, are not conducive to achieving goals (Nigg, 2000) (see Section 1.2.1.1 and Section 1.2.1.2 for a detailed discussion of these executive skills). These two abilities have been shown to relate to mathematical ability in seven-year-olds (Bull & Scerif, 2001), and inhibition has been strongly linked to English, mathematics, and science in eleven- and twelve-year-olds (St Clair-Thompson & Gathercole, 2006). Furthermore, in seven- to fourteen-year-olds, executive functions are reliable predictors of academic success (i.e. literacy, mathematics and science) (Gathercole, Brown & Pickering, 2003; Jarvis & Gathercole, 2003; St Clair-Thompson & Gathercole, 2006).

However, findings in this field are variable. For example, van der Ven et al. (2012), in a study of 211 seven- and eight-year-olds, found that, when controlling for updating ability, inhibition and task-switching did not predict mathematics. Van der Sluis et al. (2007) examined the contributions of inhibition, task-switching and updating to reading, arithmetic and non-verbal reasoning in nine- to twelve-years-olds. No inhibition factor was identified, but task-switching related to non-verbal reasoning and reading, whereas updating (i.e. WM) related to all three HLC measures. Variance in reading and mathematics was better explained by non-executive elements derived from the executive measures. For example, in an inhibition task that required participants to count the quantity of a number (e.g. three 4s), the non-executive task was counting, and the executive task was the inhibition of the automatic response of reading out the number 4. Van der Ven et al. (2012) concluded that previous studies reporting a link between task-switching and HLC have, in part, identified a relationship between the non-executive component of the measure and higher-order cognitive abilities.

As is evident from the research cited here, the structure and developmental status of inhibition and task-switching in seven- and eight-year-olds, and the relationships with HLC are, as yet, not clearly defined in the field of cognitive and developmental psychology. Findings linking inhibition and task-switching to HLC have been primarily restricted to studies that have used single measures to represent each of these abilities (e.g. Bull & Scerif, 2001); whereas studies that have failed to find relationships have used multiple measures to create latent variables. This suggests that studies using single measures of inhibition and task-switching may have found spurious links with HLC, having tapped an ability related more to non-executive abilities (see van der Sluis et al., 2007). This would be consistent with the task impurity problem discussed in Section 1.2.1. Further research is required on whether measures of working memory, inhibition and/or task-switching are the best predictors of HLC. With the aim of identifying only robust links with HLC, the investigations in the current chapter aimed to create latent variables to examine how inhibition and task-switching relate to HLC in seven- and eight-year-olds.

6.3 Research Questions

How do task-switching and inhibition relate to the underlying mechanisms of CSTs (i.e. storage, processing time, recall time, processing accuracy) when CSTs are computer-paced compared to when they are experimenter-led?

Does variance in HLC accounted for by task-switching and inhibition (i.e. over and above that accounted for by CST performance) differ when the CSTs are computer-paced compared to when they are experimenter-led?

The predictions for this study were as follows:

a) Measures of inhibition and task-switching would be related to storage performance on CSTs in both conditions due to the role of these executive skills in WM

b) Both executive abilities would relate to processing times indicating the importance of processing speed in task-switching and inhibition

c) Inhibition and task-switching would be related to academic ability indicating the importance of these abilities in activities such as mathematics and reading

d) Also, because of the importance of processing time in the computer-paced tasks, and the link between processing speed and executive control, and HLC, there was a possibility that variance accounted for in HLC by task-switching and inhibition would be affected by administration condition

6.4 Method

6.4.1 Design

This study employed a correlational design to identify the roles of task-switching and inhibition in CST performance, and the roles of all three constructs (working memory, inhibition and task-switching) in HLC. There was also intent to create latent variables for the two executive measures as it was felt that previous research that had found links between inhibition and HLC, and task-switching and HLC were limited (e.g. Bull & Scerif, 2001; Passolunghi et al., 1999). This was based on measurement of executive abilities being problematic (see Section 1.2.1 for a discussion of the task impurity problem). It was decided that the use of latent variable analysis would provide a more robust measure of these two executive abilities and could, therefore, address some of the variability in previous studies, both in terms of methodology and findings. Thereafter, hierarchical regression was used to determine which executive abilities accounted for variance in each HLC when controlling for the influence of storage, processing time, recall time and processing accuracy in CSTs. This was conducted for the Counting, Listening and Odd One Out Span tasks in both the experimenter-led and computer-paced CST conditions.

6.4.2 Participants

The sample for this study was the same as that used in Chapter Four and Five. All children were unfamiliar with the assessments prior to commencement of testing.

6.4.3 Equipment

The equipment used in this study was consistent across all studies in this thesis (please see Chapter Three for full details).

6.4.4 Measures

This study assessed all participants with regard to their individual WM, HLC and central executive abilities. WM was measured using three CSTs; namely Counting, Listening and Odd One Out Span. These were administered in both an experimenter-led and a computer-paced condition. HLC was measured using tests of non-verbal reasoning, reading and mathematics. There were also three measures of task-switching, and three measures of inhibition. The measures assessing task-switching were Creature Counting (TEA-Ch; Manly et al., 2001), the Dimensional Change Card Sort task (DCCS; Zelazo, 2006) and the Colour Number Switch (CNS) which was based on the Trail Making Test used in previous research (e.g. McLean and Hitch, 1999). The measures assessing inhibition were Walk / Don't Walk task (TEA-Ch; Manly et al., 2001), and the Verbal Inhibition Motor Inhibition task (VIMI; Henry, Messer & Nash, 2012). The specific details of all tasks are set out in Chapter Three.

6.4.5 Procedure

All the participants were tested individually in a quiet room at school, during class times in the school day. Full details of the testing sequence can be found in Chapter Three.

6.5 Results

Due to the number of variables in this chapter (i.e. 3 x inhibition, 3 x task-switching, 6 x WM), the α level for significance was reviewed to minimize the risk of Type One errors. As a Bonferroni adjustment was considered too conservative given the number of measures (Bland & Altman, 1995), a decision was made to set the α level at p <.01 (for a similar methodology see Geary et al., 2007).

6.5.1 Data Exploration Procedures

For the measures tapping inhibition and task-switching, there were issues regarding normal distributions. As the intention was to use these measures to produce latent variables, stringent procedures were undertaken to ensure normally distributed data, and appropriate levels of skewness and kurtosis. Each measure was subjected to the following manipulations to assess which would be the best method to establish normality; trimming, winsorizing, log transformation, square root transformation. This was done to identify whether the same method of adjustment could be used for each measure. A summary of the optimal manipulations chosen for each measure, along with the means and standard deviations for performance on the task-switching and inhibition measures are shown in Table 6.1. The processes for each measure are described in detail in Appendix D

***Table 6.1** Summary of means, SDs, and ranges for task-switching and inhibition measures.*

	Manipulation	Mean	*SD*	Range
Task-switching				
Creature Counting[a]	None	10.65	*3.11*	3 – 19
DCCS[b]	Single highest and lowest trimmed	29.10	*13.40*	1.90 – 75.00
CNS[c]	Single highest and lowest winsorized to 2.5 sd value	19.03	*8.68*	1.40 – 39.43
Inhibition				
Walk / Don't Walk[d]	Square root transform	2.43	*.50*	1.73 – 3.74
Verbal inhibition[e]	Square root transform + lowest score	6.04	*1.10*	3.52 – 9.60
Motor inhibition[f]	Log transform + 1	0.79	*0.31*	0.30 – 1.65

Note: Scoring for each measure was as follows: [a] = standardised ability scores; [b] = time cost; [c] = time cost; [d] = total trials correct; [e] = time cost; [f] = total errors

6.5.2 Correlations between measures of task-switching and inhibition

Pearson correlation coefficients were conducted to identify the relationships between the three task-switching measures and the three inhibition measures. It should be noted that some of the correlations were negative due to the scoring method. Specifically, a high score on the WDW and Creature Counting tasks indicated better performance as the scores were calculated by total trials correct (WDW) or standardised so that a higher score indicated higher ability (Creature Counting). A high score on the DCCS, CNS, Verbal and Motor inhibition tasks indicated poorer performance as the scores were calculated by total errors (Motor inhibition) or total time cost (DCCS, CNS, Verbal inhibition). However, there were no correlations between any of the measures. As a result the creation of latent variables was not possible. All correlations are shown in Table 6.2.

Table 6.2 *Correlations between all inhibition and task-switching measures.*

Task	Ability	1	2	3	4	5	6
1. Creature Counting	Task-switching	-	.069	-.115	.149	-.039	-.074
2. DCCS			-	-.063	.089	.030	-.029
3. CNS				-	.009	.168	.039
4. Walk / don't walk	Inhibition				-	.041	-.080
5. Verbal inhibition						-	.171
6. Motor inhibition							-

6.5.3 Correlations between the complex span task mechanisms and measures of task-switching and inhibition

Pearson correlation coefficients were conducted to identify relationships between measures of task-switching, inhibition and the CST mechanisms (i.e. storage; processing time; recall time and processing accuracy). Correlations in the experimenter-led condition are presented first, followed by correlations in the computer-paced condition.

With regard to task-switching, in the experimenter-led condition the Creature Counting task correlated with storage in the Counting Span (r = .43, p < .01) and the Odd One Out Span (r = .37, p < .01). This indicated that high performance on the Creature Counting task related to high span scores in Odd One Out and Counting Span. Creature Counting also showed significant correlations with processing time (r = -.37, p < .01) and recall time (r = -.35, p < .01) in the Counting Span task and with processing accuracy (r = .32, p < .01) in the Odd One Out Span task. These findings showed that higher scores on the Creature Counting task (i.e. better switching ability) were linked to faster processing and recall times in the Counting Span task and with greater processing accuracy in the Odd One Out Span task. The colour-number switch task related to recall time in the Counting (r = .28, p < .01) and Odd One Out Span (r = .35, p < .01) tasks. This demonstrated that faster recall times in these two tasks related to increased switching ability in the colour-number switch task. There were no correlations between measures of task-switching and Listening Span.

Significant correlations between measures of inhibition and CST performance were shown between the Verbal Inhibition task and recall time in the Counting Span task (r = .30, p < .01) and Odd One Out Span task (r = .31, p < .01). This showed that better inhibition ability on the Verbal Inhibition task related to faster recall times in Counting and Odd One Out Span. Performance on the Verbal inhibition task also related to processing times in Listening Span (r = .29, p < .01). This indicated that higher performance on this inhibition task was linked to faster processing times in Listening Span. WDW task related to storage (r = .29, p < .01) in the Listening Span task, indicating that greater inhibition on the WDW task related to higher span scores in Listening Span.

Links between task-switching and the mechanisms of CSTs were evident in the computer-paced condition, with Creature Counting correlating with processing time in Counting (r = -.41, p < .01) and Odd One Out Span (r = -.31, p < .01). This showed that better performance on the Creature Counting task related to faster processing times in Counting and Odd One Out Span. Creature Counting also related to recall time in Counting Span (r = -.45, p < .01) and Listening Span (r = -.38, p < .01). This indicated that faster recall time in these two CSTs was linked to better switching ability in the Creature Counting task. Higher scores in Creature Counting also related to higher span scores in Counting Span (r = .37, p < .01) and in Odd One Out Span task (r = .45, p < .01). The colour-number switch task showed a significant correlation with storage in the Counting Span task (r = -.28, p < .01), indicating that high scores on this switch task related to high span scores in Counting Span. The colour-number switch also related to processing time in the Listening Span task ($r = .31$, $p < .01$), which showed that faster processing times were linked to better switching ability on this task.

Measures of inhibition related to CSTs in the computer-paced condition with the Verbal Inhibition task correlating with processing time in Listening ($r = .32$, $p < .01$) and Odd One Out Span ($r = .31$, $p < .01$) tasks. This indicated that faster processing times in these two CSTs were associated with better inhibition performance in the Verbal Inhibition task. There were no other significant correlations.

All correlations for the experimenter-led and computer-paced tasks are shown in Table 6.3 and Table 6.4 respectively. Significant correlations are in bold and highlighted in yellow and indicated by asterisks.

Table 6.3 *Correlations between Inhibition and task-switching measures and CST mechanisms for the experimenter-led condition*

	Counting Span				Listening Span				Odd One Out Span			
EF Measures	Storage	P. time [a]	R. time [b]	P. acc [c]	Storage	P. time	R. time	P. acc	Storage	P. time	R. time	P. acc
CC	**.426****	**-.369****	**-.351****	-.071	.197	-.131	.229	.088	**.367****	-.212	-.313**	**.320****
DCCS	.003	.022	-.123	.040	-.018	-.153	-.019	-.048	.063	-.120	-.203	.050
CNS	-.183	.190	**.275****	-.067	-.144	.185	.055	.181	.125	.137	**.348****	.115
WDW	.215	- .140	.033	.040	**.291****	-.032	.135	.094	.170	.094	.064	.067
VI	-.075	.162	**.299****	-.085	-.078	**.288****	.168	-.074	-.154	.275	**.308****	.081
MI	-.133	.088	.127	-.045	-.260	.095	.043	-.044	-.060	.028	.064	-.088

EF = executive function, CC = Creature Counting; DCCS = Dimensional Change Card Sort; CNS = Colour-number Switch; WDW = Walk / Don't Walk; VI = Verbal Inhibition; MI = Manual Inhibition

[a] = processing time; [b] = recall time; [c] = processing accuracy

** *p* < .01

Table 6.4 *Correlations between for Inhibition and task-switching measures and CST mechanisms for the computer-paced condition*

	Counting Span				Listening Span				Odd One Out Span			
EF Measures	Storage	P. time [a]	R. time [b]	P. acc [c]	Storage	P. time	R. time	P. acc	Storage	P. time	R. time	P. acc
CC	**.369****	**-.406****	**-.453****	.132	.224	-.196	**-.376****	.041	**.451****	**-.307****	-.161	-.038
DCCS	.060	.036	-.056	-.048	.067	-.004	.072	.155	.109	.244	.112	.255
CNS	**-.284****	.033	.245	-.108	-.143	**.312****	.180	-.065	-.190	.067	.132	.027
WDW	.251	-.201	-.047	-.057	.048	-.049	-.063	.125	.111	-.030	.182	.026
VI	-.163	.123	.205	-.106	-.137	**.324****	.151	-.223	-.163	**.306****	.170	-.152
MI	-.241	.009	.136	.021	-.195	.094	.107	-.226	-.067	.070	-.036	-.032

EF = executive function; CC = Creature Counting; DCCS = Dimensional Change Card Sort; CNS =Colour-number Switch; WDW = Walk / Don't Walk; VI = Verbal Inhibition; MI = Manual Inhibition

[a] = processing time; [b] = recall time; [c] = processing accuracy

** $p < .01$

6.5.4 Correlations with high-level cognition

Pearson correlation coefficients were calculated to assess the relationship between inhibition and task-switching measures and HLC (i.e. non-verbal reasoning, reading and mathematics). None of the inhibition measures demonstrated a significant correlation with any of the HLC measures. For task-switching, the Creature Counting task showed a significant correlation with reading (r = .32, p < .01) and with mathematics (r = .41, p < .01). All correlations are shown in Table 6.5.

Table 6.5 *Correlations between Inhibition and task-switching measures and measures of HLC.*

Task	Non-verbal reasoning	Reading	Mathematics
Creature Counting	.249	**.317****	**.413****
DCCS	.048	.060	-.017
CNS	.094	.252	.125
Walk Don't Walk	.049	-.154	.130
Verbal Inhibition	-.059	-.010	-.152
Motor Inhibition	-.111	-.085	-.187

** p < .01

6.5.5 Executive skills and high-level cognition

The second objective of the current study was to identify whether the inclusion of measures of task-switching and inhibition would further explain the relationship between WM performance and HLC, beyond that accounted for by the CST mechanisms examined in Chapter Five. As measures of inhibition did not demonstrate significant correlations with each other or with any of the measures of HLC, the construct was removed from further analysis. Furthermore, as the two of the task-switching measures (i.e. CNS and DCCS) did not correlate with each other or the Creature Counting measure, and failed to correlate with any of the HLC measures, they were also excluded from further analyses. Therefore, hierarchical regression was conducted wherein the four mechanisms of the CSTs (i.e. storage, processing time, recall time, processing accuracy) were entered into Step 1 of the model and task-switching (i.e. measured by performance on the Creature Counting task) was entered into Step 2. This was conducted for both administration conditions across all three CSTs for each measure of HLC.

The information in Table 6.6 includes total variance accounted for (total R^2) in non-verbal reasoning by each CST and by Creature Counting. The standardised β values are also provided. Data are only included for those models where the total variance explained was significant. The regression results for Step 1 (i.e. storage, processing time, recall time, processing accuracy) are a replication of the regression analyses produced and discussed in Chapter Five. They are included here in Step 1 to control for their contribution to HLC only. Therefore only regression statistics for Step 2 are provided. Also, to allow for easy interpretation, for Step 2 only significant β values are provided (in italics beneath Step 2). Significant values are in bold and indicated with asterisks where relevant.

Table 6.6 *Summary of hierarchical regression for CSTs (step 1) and Creature Counting (Step 2) predicting non-verbal reasoning.*

Predictor variable	**Total R^2**	**Change in R^2**	***F* Change**	**β**
Counting				
EL	**.22****			
Step 1:		**.22****	**4.88****	-
Step 2:		<.001	.05	-
CP	**.33*****			
Step 1:		**.30*****	**9.28*****	-
Step 2:		.03	3.17	-
Listening				
EL	**.17****			
Step 1:		.11	2.63	-
Step 2:		.06	5.93	-

***p*<.01; ****p*<.001

EL = experimenter-led condition, CP = computer-paced condition

Step 1: storage, processing time, recall time, processing accuracy; Step 2: Creature Counting

The information in Table 6.7 includes total variance accounted for (total R^2) in reading ability by each CST and by Creature Counting. The standardised β values are also provided. Data are only included for those models where the total variance explained is significant. As the regression results for Step 1 are included in the previous chapter, only regression statistics for Step 2 are provided. Also for Step 2, only individual significant β values are provided (in italics beneath Step 2). Significant values are in bold and indicated with asterisks where relevant.

Table 6.7 *Summary of hierarchical regression for CSTs (step 1) and Creature Counting (Step 2) predicting reading.*

Predictor variable	**Total R^2**	**Change in R^2**	***F* Change**	**β**
Counting				
EL	**.19****			
Step 1:		**.18****	**4.62****	-
Step 2:		.02	1.56	-
CP	**.25*****			
Step 1:		**.19****	**4.93****	-
Step 2:		.06	6.84	-

** p<.01; ***p<.001

EL = experimenter-led condition, CP = computer-paced condition

Step 1: storage, processing time, recall time, processing accuracy; Step 2: Creature Counting

The information in Table 6.8 includes total variance accounted for (total R^2) in mathematical ability by each CST and by Creature Counting. The standardised β values are also provided. Data are only included for those models where the total variance explained is significant. As the regression results for Step 1 are included in the previous chapter, only regression statistics for Step 2 are provided. Also for Step 2, only individual significant β values are provided (in italics beneath Step 2). Significant values are indicated with asterisks where relevant.

Table 6.8 *Summary of hierarchical regression for CSTs (step 1) and Creature Counting (Step 2) predicting mathematics.*

Predictor variable	**Total R^2**	**Change in R^2**	**F Change**	**β**
Counting				
EL	**.44*** **			
Step 1:		**.42*** **	**15.35*** **	-
Step 2:		.03	3.80	-
CP	**.52*** **			
Step 1:		**.49*** **	**20.76*** **	-
Step 2		.02	4.09	-
Listening				
EL	**.27*** **			
Step 1:		**.18** **	**4.57** **	-
Step 2:		**.09** **	**10.90** **	-
Task-switching				**.33** **
CP	**.23** **			
Step 1:		**.15** **	**3.60** **	-
Step 2:		**.08** **	**8.58** **	-
Task-switching				**.31** **

Continued on next page....

Predictor variable	Total R^2	Change in R^2	*F* Change	β
Odd one out				
EL	**.24****			
Step 1:		.09	1.5	-
Step 2:		**.15****	**12.53****	-
Task-switching				**.47****
CP	**.33*****			
Step 1:		**.34*****	**9.19*****	-
Step 2:		.02	2.32	-

**p<.01; ***p<.001

EL = experimenter-led condition, CP = computer-paced condition

Step 1: storage, processing time, recall time, processing accuracy; Step 2: Creature Counting

To assess whether the Creature Counting measure accounted for variance in HLC over and above storage ability in all six of the CSTs, hierarchical regression was conducted wherein total trials correct (TTC) for each of the three CSTs (i.e. Counting, Listening and Odd One Out Span) in each administration condition (i.e. experimenter-led, computer-paced) were entered into Step 1 of the model and the standardised score from the Creature Counting measure was entered into Step 2.

The information in Table 6.9 includes total variance accounted for (total R^2) in each measure of HLC (i.e. non-verbal reasoning, reading, mathematics) by all six CSTs and by Creature Counting. The standardised β values are also provided. Data are only included for those models where the total variance explained was significant. The regression results for Step 1 (i.e. Counting, Listening and Odd One Out Span) are a replication of the regression analyses produced and discussed in Chapter Five. They are included here in Step 1 to control for their contribution to HLC only. Significant values are indicated in bold, with asterisks where relevant.

Table 6.9 *Summary of hierarchical regression for all CSTs and Creature Counting predicting HLC.*

Outcome variable	**Total R^2**	**Change in R^2**	**F Change**	**β**
Non-verbal reasoning	**.23****			
Step 1:		**.23****	**4.06****	-
Step 2:		<.001	0.02	-.02 (p = .88)
Reading	**19***			
Step 1:		**.15***	**2.39***	-
Step 2:		**.05***	**4.76***	**.25***
Mathematics	**.48*****			
Step 1:		**.48*****	**12.50*****	-
Step 2:		.06	2.50	.14 (p = .12)

*p,.05; **p<.01; ***p<.001

Step 1: TTC for experimenter-led and computer-paced versions of Counting, Listening, Odd One Out Span. Step 2: Creature Counting

6.5.6 Summary of regression analyses

Performance on the Creature Counting task did not account for a significant amount of further variance in non-verbal reasoning or reading ability. Significant variance in mathematics was accounted for by performance on the Creature Counting task after controlling for performance on the CST mechanisms in the experimenter-led (r^2 = .9, p < .01; β = .33, p < .01) and computer-paced (r^2 = .8, p < .01; β = .31, p < .01) versions of the Listening Span task, and in the experimenter-led version of the Odd One Out Span task (r^2 = .15, p < .01; β = .47, p < .01).

Performance on the Creature Counting task did not account for a significant amount of further variance in non-verbal reasoning or mathematics ability after controlling for storage ability in all six CSTs. Significant variance in reading was accounted for by performance on the Creature Counting task (i.e. after controlling for performance on the six CSTs), but this was only significant when α was set at .05 (change in r^2 = .05, $p < .05$; β = .25, $p < .05$). Consistent with the α adjustment to .01 in Chapter, this finding should not be considered significant.

6.6 Discussion

The aim of this study was two-fold. Firstly, performance on task-switching and inhibition tasks were examined to determine whether their possible relationships with the underlying mechanisms of CSTs were altered when the processing duration of the CSTs was time-restricted compared to when it was not. Second, the relationships between task-switching and HLC, and inhibition and HLC were investigated to identify whether task-switching and inhibition would account for variance in HLC over and above that accounted for by the CSTs.

Consistent with the findings of Huizinga et al. (2006) and van der Sluis et al. (2007) the measures designed to assess inhibition did not correlate with each other. Furthermore, inhibition was not linked to any measures of HLC, which also replicated findings in previous research with adults (Friedman et al., 2006) and children (Toll et al., 2011; van der Sluis et al., 2007; van der Ven et al., 2012). This finding may be explained by the Hasher et al. (2007) theory of inhibition discussed in Section 1.2.1.1, which argues that inhibition is not a single construct, but a series processes important in WM. Indeed, cognitive inhibition (including automatic and intentional), behavioral inhibition, and resistance to interference have all been labeled as inhibition in various studies (e.g. Bull & Scerif, 2001; Passolunghi et al., 1999), but may be seen as three distinguishable abilities. Furthermore, results from other studies have indicated that inhibition has various manifestations dependent upon the defined behaviour. In a review of cognitive deficit measurement in attention-deficit/hyperactivity disorder (ADHD) patients, Kipp (2005) proposed three measurable behaviours that had instead been grouped into a single inhibition construct in previous research. Further, Nigg (2000) argued that executive, motivational, and automatic attentional inhibitory processes are all distinguishable from each other.

Looking at previous research on the relationships between inhibition and HLC in terms of these distinctions may shed light on the current findings. For example, Passolunghi et al. (1999) found inhibition to be indicative of poor problem-solving skills. However, the study did not use a specific measure of inhibition, but rather, measured the ability to reject irrelevant information in a WM task. Such an inhibitory ability would likely be considered resistance to interference (Kipp, 2005) or automatic attentional inhibition (Nigg, 2000). Bull and Scerif (2001) found a link between inhibition and mathematics ability, but used only one measure of the construct (i.e. Stroop task), which may be a measure of cognitive/intentional (Kipp, 2005) or executive (Nigg, 2000) inhibition. This point relates to the initial objective of this chapter, which was to create latent variables for both inhibition and task-switching in order to lessen the possibility of task impurity. Executive abilities are difficult to measure as they inevitably involve other cognitive processes (e.g. phonological processing, visual STM), and when only one task is used to represent, for example inhibition, performance is also indicative of other capacities. Therefore, it is entirely possible that findings using single measures are identifying a link between another cognitive construct (or constructs) and not the intended executive ability.

Considering that other studies using multiple measures of inhibition (Friedman et al., 2006; Toll et al., 2011; van der Sluis et al., 2007; van der Ven et al., 2012), have not found links with HLC, it may be that studies using a single measure (Bull & Scerif, 2001) or indicators (Passolunghi et al., 1999) have found spurious links which were possibly due to the influence of other WM factors. For example, the study by Passolunghi et al. found intrusions in a Listening Span task were linked to lower problem solving ability. These intrusions were calculated as the number of times the wrong words were recalled from the sentences in the processing component of the task (i.e. not the last word, but a word within the sentence). However, the intrusions may have been indicative of reduced recall ability, and poor use of semantic cues to aid recall (Cowan et al., 2003), as opposed to interference from other sentence words. As no other CSTs were used in the study, it was not possible to know whether poor recall would have been similar in other tasks such as Counting or Odd One Out Span.

Measures of inhibition (i.e. the verbal inhibition from VIMI) did correlate with processing times in Listening Span and Odd One Out Span in the computer-paced condition. This was consistent with the prediction that inhibition would be important in WM recall when maintenance opportunities were minimized (Rose et al., 2011). However, this was also the finding for the experimenter-led Listening Span task, which was not expected due to the maintenance opportunity afforded by the unrestricted processing times. In addition, this finding was not evident for any other measures of inhibition.

Scores on the Walk/Don't Walk task were related to storage in the experimenter-led version of Listening Span. This was consistent with the prediction that inhibition would be related to WM scores due to its role in filtering out irrelevant information and resisting distraction (Baddeley, 2002). However, again, links between storage and other measures of inhibition were not found.

The absence of links between the inhibition tasks, the fact that there were no links with HLC, and that links with storage and processing were sparse, led to the conclusion that this study did not find evidence of inhibition playing a role in HLC. This was consistent with findings from research with adults (Friedman et al., 2006) and the aforementioned studies with children (Toll et al., 2011; van der Sluis et al., 2007; van der Ven et al., 2012).

Two of the task-switching measures (i.e. CNS and DCCS) did not correlate with each other or with the third task-switching measure, Creature Counting. However, Creature Counting was related to storage scores in both versions of

Counting Span, and Odd One Out Span. This was consistent with findings indicating that an ability to switch back to memory items more quickly leads to reduced memory decay and better recall (Conway & Engle, 1996; Towse & Hitch, 1995; Towse et al., 1998). In Counting Span, faster processing times related to task-switching in both administration conditions, and in the computer-paced condition for Odd One Out Span. This relationship between task-switching and processing times was consistent with research findings that have shown a strong relationship between processing speed and task-switching functions (Rose at al., 2011; but see Cepeda et al., 2013).

Performance on the Creature Counting task was related to reading and mathematics, showing that better task-switching ability was linked to higher scores on the reading and maths tasks. Furthermore, task-switching accounted for variance in mathematics over and above that accounted for by CST performance from all four mechanisms (i.e. storage, processing time, recall time, processing accuracy). This was evident in the both versions of the Listening Span task, and in the experimenter-led version of the Odd One Out Span task, and was consistent with the prediction that task-switching would be related to HLC. However, as the cognitive requirement for the Creature Counting task was based on counting ability, it is entirely possible that the variance accounted for by this task (i.e. and not from either of the other two task-switching tasks, or from all three inhibition tasks) was from counting, rather than switching ability.

Having addressed possible reasons for the absence of a link between inhibition and HLC, it is important to understand why the other measures of task-switching did not correlate with each other, or any measures of HLC even though reliability for all three measures was good. One difference may be the preparation time allowed in each task. For the Creature Counting task, preparation was minimal. The participant undertook two short practice trials before proceeding to the test trials, each of which had the switching paradigm built into them (i.e. switching between counting up and counting down). However, the DCCS and the CNS both had several sets of non-switch trials (i.e. two trials and three trials respectively) before the switching paradigm was introduced (i.e. switching between colour and number for CNS and switching between sort rules in CNS). Research by Cepeda, Kramer, Gonzalez de Sather (2001) has shown that children benefit from longer preparatory intervals within switch tasks (i.e. between target cue and task stimulus). This, it was argued, was because it provided more time to become familiar with the stimuli in preparation for the task. In the CNS and DCCS tasks there were opportunities for preparation in the non-switch trials, which were not available in the Creature Counting task. Although this did not occur immediately before presentation of the incongruent tasks and cannot therefore be directly compared to the findings by Cepeda at al., it is possible that familiarity of task stimuli lessened the effect of switch costs and therefore reduced correlations with Creature Counting and measures of HLC.

6.7 Executive summary

The current study was able to identify neither an inhibition nor a task-switching latent variable using several measures of each ability. When scores on the individual measures were examined, there were a few links with storage and processing time in the WM tasks, but this was not consistent cross the executive tasks. Furthermore, variance in HLC above and beyond that accounted for by the WM tasks was only evident for mathematics ability, and came from a single task (i.e. Creature Counting). As this task was dependent on counting ability it is possible that this was due to the link between mathematics and counting, and not task-switching ability. In summary, findings from the current study were consistent with those from existing research that have failed to find a strong link between HLC and the executive abilities of inhibition and task-switching over and above contributions from WM tasks (e.g. van der Sluis et al., 2007; van der Ven et al., 2012).

7 Chapter Seven: A Longitudinal Study of the Relationship Between Working Memory and Mathematics Ability

7.1 Chapter Overview

The previous three chapters demonstrated that temporal constraints within complex span tasks influence the various relationships between their underlying mechanisms (i.e. storage, processing time, recall time, processing accuracy), and high-level cognition. The importance of early identification of the predictors of higher-order cognitive abilities in children is now considered, as the current chapter addresses the final question in this thesis: How does working memory relate to mathematics ability two years later; i.e., is it possible to predict mathematics ability longitudinally based on earlier cognitive abilities?

7.2 Research Rationale

The previous three chapters investigated the relationship between working memory (WM), and high-level cognition (HLC). Chapter Four demonstrated that restricting the time allowed for processing stimuli in complex span tasks (CSTs) affected how they related to HLC. When the underlying mechanisms of the CSTs (i.e. storage, processing time, recall time, processing accuracy) were examined in Chapter Five it was found that some of the mechanisms in the experimenter-led versions of the tasks that accounted for variance in HLC were different to the mechanisms in the computer-paced versions. Chapter Six considered the relationships between inhibition, task-switching, the mechanisms of CSTs and HLC. A single task-switching measure (i.e. Creature-Counting) showed the strongest and most consistent relationship with the CSTs and with HLC.

The HLC measure that demonstrated the strongest relationship with WM across all three studies was mathematics. In Chapter Four, mathematics was significantly related to WM span scores in each CST, and these relationships were stronger compared to those with non-verbal reasoning and reading. Furthermore, when all the underlying mechanisms of the CSTs (i.e. storage, processing time, recall time, processing accuracy) were considered in Chapter Five, they also accounted for more total variance in mathematics than in non-verbal reasoning and reading. A summary of the results can be seen in Table 7.1. Only significant values are shown.

Table 7.1. *Summary of Chapter Five regressions: Percentage of variance in HLC accounted for by each CST, including all mechanisms.*

Task		Non-verbal reasoning	Reading	Mathematics
Counting Span				
	EL	**19%**	**15%**	**42%**
	CP	**30%**	**19%**	**49%**
Listening Span				
	EL	-	-	-
	CP	-	-	**15%**
Odd One Out Span				
	EL	-	-	-
	CP	-	-	**34%**

EL = experimenter-led, CP = computer-paced

Furthermore, in Chapter Six, mathematics ability was the only HLC measure that related to task-switching, with Creature Counting accounting for variance in mathematics when controlling for all CST mechanisms. This was the case for the experimenter-led and the computer-paced versions of the Listening Span task and the experimenter-led version of the Odd One Out Span task. These findings suggest that mathematics ability is strongly related to WM. A brief summary of findings from previous studies is provided as a foundation for the investigation in the current chapter.

7.3 Brief summary of the literature

Many functions, such as the temporary storage of numbers, flexibility of strategy use and inhibition of irrelevant information are required in mathematical processing, and there is much research evidence to support the assumption that WM plays an important part in the development of this skill (Adams & Hitch, 1997; Alloway & Passolunghi, 2011; Berg, 2008; Bull & Scerif, 2001; Cowan et al., 2011; Henry & MacLean, 2003; Holmes & Adams, 2006; McLean & Hitch, 1999).

Previous studies have demonstrated specific relationships between mathematical performance and both phonological WM (De Smedt et al., 2010; Hecht et al., 2001) and visuospatial WM (Krajewski & Schneider, 2009b; Passolunghi & Mammarella, 2011). A longitudinal study by Hecht et al. (2001), for example, examined the relationship between phonological processing and computation skills in seven- to eleven-year-old school children, finding that phonological WM was strongly related to general computation ability and, in turn, to arithmetic problem solving. Others have found that visuospatial WM predicts mathematical ability two years later in seven- and eight-year-olds (Li & Geary, 2013) and six- to sixteen-year-olds (Dumontheil & Klingberg, 2012). Li and Geary (2013) also showed that numerical and visuospatial processing speeds, in addition to visuospatial WM, in seven- and eight-year-olds were predictive of mathematical ability in nine- and ten-year-olds.

With regard to task-switching and inhibition, findings tend to vary. For example, task-switching and inhibition have been shown to play a role in mathematical difficulties in six- to eight-year-olds (Bull & Scerif, 2001), but only task-switching (i.e. not inhibition) was been found to contribute to maths ability in eleven- and twelve-year-olds (St Clair-Thompson & Gathercole, 2006). However, van der Ven et al. (2012) found updating to be a strong predictor of early mathematics in seven to eight year-olds, but inhibition and switching were not,. Bull et al. (2008) found working memory to be the best predictor of maths in seven year-olds, whereas inhibition and switching were more likely to predict learning generally. Yet Toll et al. (2011) found that performance on measures of inhibition and working memory related to differences in mathematical ability in six-year-olds.

This review indicates that the link between WM and mathematics is strong; and it is therefore argued that contributions to a greater understanding of what drive mathematical learning are important. For example, studies have shown early intervention to be the most effective approach to addressing mathematical learning difficulties in children (Holmes et al., 2009; Kroesbergen et al., 2012). However, few studies have examined the underlying mechanisms of CSTs with regard to their longitudinal relationship with mathematics (but see Geary et al., 2007). Also, no studies have compared performance on experimenter-led and computer-paced CSTs and investigated their relationships with future mathematics ability. Therefore, the current chapter investigated how WM ability in Year 3 related to mathematics performance two years later, using the novel measures of WM, with the purpose of identifying specific longitudinal predictors of this academic ability. The mathematics test used (Access Mathematics Test; McCarty, 2008) linked directly to the key learning concepts dictated by the UK National Curriculum (i.e. calculation, problem solving, shape, space and measure). These learning concepts are provided in detail in Appendix J.

7.4 Research Questions

Can measures of WM at the age of seven- to eight-years predict mathematical ability at the age of nine- to ten-years?

What are the respective influences of WM (i.e. numerical, verbal, visuospatial), underlying CST mechanisms (i.e. storage, processing time, recall time, processing accuracy), and administration conditions (i.e. computer-paced and experimenter-led)?

The predictions for the current study were consistent with findings from previous research (e.g. Li & Geary, 2013; Dumontheil & Klingberg, 2012; see Section 2.4 and Section 7.3). However, the tasks used for the measurement of WM here offer a unique contribution to the research field, particularly given the importance of processing speeds identified by other researchers:

a) Visuospatial and numerical WM storage in seven- to eight-year-olds would predict Year 5 mathematical ability.

b) Numerical and visuospatial WM processing speed in seven- and eight-year-olds would predict Year 5 mathematical ability.

c) With regard to the longitudinal predictive strength of the computer-paced tasks compared to the experimenter-led tasks, the lack of research in this area made it difficult to formulate a prediction; however it was considered that, consistent with the findings in Chapter Five, storage in the experimenter-led condition and processing time in the computer-paced condition would predict mathematics two years later.

d) Given the findings from Chapter 6, it was not expected that there would be relationships between Year mathematics and the executive abilities; task-switching and inhibition.

7.5 Method

7.5.1 Design

This was a longitudinal study that employed a multivariate design to identify the relationships between WM in Year 3 and mathematical ability in Year 5. Year 3 performance in the four CST mechanisms (i.e. storage, processing time, recall time, processing accuracy) for all CSTs (in both the experimenter-led and computer-paced CST conditions), and on measures of task-switching and inhibition were assessed in terms of their relationship to mathematics ability in Year 5. Regression analyses were used to determine which Year 3 abilities accounted for variance in Year 5 mathematics.

It is noted that WM itself, and other abilities such as reading and IQ would have developed in the period between testing in Year 3 and again in Year 5, and the benefit of measuring these abilities again in Year 5 would indeed be informative. However, the time constraints that are unavoidable in a three-year PhD timeframe meant that re-assessing all participants on WM was not feasible, and therefore a further WM assessment in Year 5 was not included in the current study.

7.5.2 Participants

The full sample for this thesis consisted of children in Year 3 of UK primary school education. As data were collected over a two-year period (i.e. two Year 3 cohorts), only data collected in the first cohort (n = 56) was relevant to this study. Therefore, children whose WM ability was measured in Year 3 during the academic year: 2012/2013 were assessed on entering Year 5 (i.e. academic year: 2014/2015). Five children had left the participating schools in the intervening academic year. Therefore fifty-one children, aged between nine and ten years, participated in this longitudinal phase of the study. All children were unfamiliar with the assessments prior to commencement of testing. Table 7.2 gives details of the sample age ranges and standard deviations at Year 3 testing time one (T1) and Year 5 testing time two (T2).

Table 7.2 *Summary of means and SDs ages in months (age in years) for testing Year 3 (T1) and Year 5 (T2)*

Variable (*n* = 51; 22 male)	Mean	*SD*	Range
Age at testing T1	94.00 (7.83 yrs)	*4.24*	86-103
Age at testing T2	112.92 (9.41 yrs)	*3.19*	108–119

7.5.3 Equipment

The equipment used in this study was consistent across all studies in this thesis (please see Chapter Three for full details).

7.5.4 Measures

Mathematics ability in Year 5 was measured using the Access Mathematics Test (AMT; McCarty, 2008). Table 7.3 shows the relationship between the components of the Access Maths test and the National Curriculum. All other tests carried out during Year 3 are as described in Chapter 3.

Table 7.3 *Access Mathematics Test performance indices mapping to mathematics strands of the National Curriculum.*

Acccess Mathematics Test	Abbreviation	National Curriculum Strand
Using and applying mathematics	UA	Understanding number
Counting and understanding number	CN	Calculation and problem solving
Knowing and using number facts	NF	
Calculating	CA	
Understanding shape	SH	Shape
Measuring	ME	Space and Measure
Handling data	HD	Handling data

7.5.5 Procedure

Testing procedures for Year 3 measures are described in the previous empirical chapters. For the Year 5 mathematics test, children completed the test in a group session as recommended in the administration manual. The minimum child to adult ratio was ten (children) to one (adult). Full details of the testing sequence can be found in Chapter Three.

7.6 Results

The raw and age-standardised scores for performance on the Access Mathematics Test are provided in Table 7.4. Scores across each of the curriculum-specific sub-areas are also provided. Decimal and group level scores for National Curriculum comparisons, as calculated from the administration manual, are included to indicate the ability range of the participants.

Table 7.4 *Summary of means, SDs, and ranges for Access Mathematics Test performance*

Variable	Mean	*SD*	Range
Raw total score	30.41	*11.82*	6-52
Standard total score	109.84	*15.77*	70-130
NC decimal level	3.78	*0.78*	2.2-5.2
NC group level	3.33	0.*82*	2-5
Raw score UA	4.06	1.99	0-7
Raw score CN	6.92	2.59	1-11
Raw score NF	4.92	1.65	1-7
Raw score CA	3.33	1.76	1-7
Raw score SH	2.98	2.18	0-8
Raw score ME	3.22	1.89	0-7
Raw score HD	4.98	2.07	0-8

NC = National Curriculum, UA = using and applying mathematics, CN = counting and understanding number, NF = knowing and using number facts, CA = calculating, SH = understanding shape, ME = measuring, HD = handling data

For reference, mean Year 3 scores on non-verbal reasoning, reading and mathematics in Year 3 are provided in Table 7.5.

Table 7.5: *Mean scores, SDs, and ranges for Year 3 HLC measures*

Variable	Measure	Mean	*SD*	Range
Non-verbal reasoning	RCPM	111.2	*16.09*	70-140
Reading	BAS III Reading	110.66	*9.7*	88-128
Mathematics	Year 3 SATs Maths	8.27	*1.37*	6-12

RCPM = Raven Coloured Progressive Matrices; BAS = British Ability Scales III; SATs = Standard Assessment Tests

7.6.1 Year 3 HLC and Year 5 mathematics ability

To compare maths performance in Year 3 to maths performance in Year 5, Pearson correlation coefficients were calculated between Year 3 academic ability and Year 5 mathematics ability. The SATs measure for mathematics ability in Year 3 demonstrated strong correlations with overall Year 5 mathematics performance. Specifically, there were strong correlations with Using and Applying Mathematics, Counting and Understanding Number, Number Facts, Calculating and Measuring. There were also moderate correlations with Shape and Handling Data. There were also moderate correlations between Year 5 maths (i.e. total score) and Year 3 non-verbal reasoning and reading ability. All correlations are shown in Table 7.6.

Table 7.6: *Correlations between Year 5 mathematics ability with Year 3 HLC*

Measure	AMT	UA	CN	NF	CA	SH	ME	HD
SATs[a]	**.830****	**.719****	**.775****	**.756****	**.797****	**.657****	**.728****	**.580****
Raven	**.380****	.337	.326	.321	.340	**.417****	.328	.308
BAS III Reading	**.402****	.308	.272	.313	.217	**.410****	.307	.266

[a] = Year 3 SATs score, AMT = Year 5 Access Mathematics Test score; UA = using and applying mathematics, CN = counting and understanding number, NF = knowing and using number facts, CA = calculating, SH = understanding shape, ME = measuring, HD = handling data

** $p < .01$

7.6.2 Year 3 WM storage scores and Year 5 mathematics

Pearson correlation coefficients were calculated for AMT total scores and the sub-area component scores in Year 5 and WM span scores in Year 3. The AMT, UA, CN and CA all were related to Counting Span in both conditions and all components related to Listening Span in the computer-paced condition. This showed that higher span scores on these CSTs related to higher ability in AMT, UA, CN and CA. Higher span scores in the computer-paced condition of all three CSTs were related to better ME scores. All correlations are shown in Table 7.7.

Table 7.7: *Correlations between comparing Year 3 CST storage and Year 5 mathematics*

WM Measure	AMT	UA	CN	NF	CA	SH	ME	HD
Counting EL	**.435****	**.474****	**.459****	.318	**.436****	.261	.263	.329
Counting CP	**.387****	**.417****	**.418****	.326	**.364****	.270	**.437****	.226
Listening EL	.274	.252	.337	.242	.306	.108	.275	.213
Listening CP	**.501****	**.397****	**.445****	**.409****	**.557****	**.429****	**.446****	**.405****
Odd One Out EL	.153	.129	-.028	.111	.168	.126	.154	.097
Odd One Out CP[6]	.403	.379	.355	.239	.325	.278	**.435****	.276

EL = experimenter-led, CP = computer-paced, AMT = Access Maths Test, UA = using and applying mathematics, CN = counting and understanding number, NF = knowing and using number facts, CA = calculating, SH = understanding shape, ME = measuring, HD = handling data

** $p < .01$

7.6.3 Year 3 WM processing time and Year 5 mathematics

Pearson correlation coefficients were calculated for Year 5 Access Mathematics total and component scores and WM processing time in Year 3. Faster processing time in both administration conditions for Counting Span was related to higher performance

[6] r values for Odd One Out Span are not significant (i.e. when α = .01) even though higher values are significant for other tasks. This is due to the reduce data points for this task (due to equipment failure) as explained in Chapter Three.

on AMT, UA, CN, NF, CA and ME. However, this relationship was only evident with SH in the computer-paced version of the task. score. Faster processing times in the computer-paced version of Odd One Out Span related to higher ability in AMT, UA, CN, SH and HD. All correlations are shown in Table 7.8.

Table 7.8: *Correlations between Year 3 processing times and Year 5 mathematics*

WM Measure	AMT	UA	CN	NF	CA	SH	ME	HD
Counting EL	**-.421****	**-.583****	**-.538****	**-.408****	**-.479****	-.292	**-.432****	-.102
Counting CP	**-.569****	**-.650****	**-.564****	**-.554****	**-.554****	**-.489****	**-.450****	-.233
Listening EL	-.236	-.119	-.251	-.296	-.360	-.111	-.242	-.134
Listening CP	-.197	-.007	-.214	-.141	-.308	-.237	-.153	-.138
Odd One Out EL	-.272	-.131	-.284	-.159	-.237	-.273	-.331	-.288
Odd One Out CP	**-.467****	**-.429****	**-.435****	-.282	-.263	**-.427****	-.346	**-.455****

EL = experimenter-led, CP = computer-paced, UA = using and applying mathematics, CN = counting and understanding number, NF = knowing and using number facts, CA = calculating, SH = understanding shape, ME = measuring, HD = handling data

** $p < .01$,

7.6.4 Year 3 recall time and Year 5 mathematics

Pearson correlation coefficients were calculated for Year 5 Access Mathematics total and component scores and WM recall time performance indices in Year 3. Only one significant correlation was identified; faster recall times in the computer-paced version of Counting Span related to higher scores on the UA measure. All correlations are shown in Table 7.9.

Table 7.9: *Correlations between Year 3 CST recall times and Year 5 mathematics*

WM Measure	AMT	UA	CN	NF	CA	SH	ME	HD
Counting EL	-.060	-.213	-.028	.001	-.140	-.062	-.063	-.078
Counting CP	-.229	**-.378******	-.314	-.193	-.196	-.135	-.210	-.098
Listening EL	.030	-.055	.016	-.048	-.049	.082	-.004	.068
Listening CP	-.203	-.322	-.208	-.129	-.287	-.191	-.329	-.103
Odd One Out EL	-.126	-.022	-.153	-.012	-.139	-.165	-.233	-.104
Odd One Out CP	-.062	-.051	-.014	-.106	-.127	-.185	.051	-.027

EL = experimenter-led, CP = computer-paced, UA = using and applying mathematics, CN = counting and understanding number, NF = knowing and using number facts, CA = calculating, SH = understanding shape, ME = measuring, HD = handling data

** $p < .01$

7.6.5 Year 3 processing accuracy and Year 5 mathematics

Pearson correlation coefficients were calculated for Year 5 Access Mathematics total and component scores and WM processing accuracy performance indices in Year 3. No significant correlations were identified. All correlations are shown in Table 7.10.

Table 7.10: *Correlations between Year 3 CST processing accuracy and Year 5 mathematics*

WM Measure	AMT	UA	CN	NF	CA	SH	ME	HD
Counting EL	.177	.237	.293	.211	.267	.160	.097	.141
Counting CP	.006	.192	.051	-.130	.001	.006	.205	.056
Listening EL	.197	.302	.223	.113	.119	.099	.159	.177
Listening CP	.291	.201	.291	.288	.184	.243	.187	.226
Odd One Out EL	.148	.087	-.021	.176	.043	.300	-.022	.117
Odd One Out CP	.011	-.173	.077	.002	.063	.091	.022	-.024

EL = experimenter-led, CP = computer-paced, UA = using and applying mathematics, CN = counting and understanding number, NF = knowing and using number facts, CA = calculating, SH = understanding shape, ME = measuring, HD = handling data

** $p < .01$

7.6.6 Year 3 inhibition, task-switching and Year 5 mathematics ability

Pearson correlation coefficients were calculated for Year 5 Access Mathematics total and component scores and Year 3 measures of task-switching and inhibition. A single significant correlation was identified between CN and the colour-number switch task, indicating that higher switching ability on this task was related to higher scores on the CN measure. All correlations are shown in Table 7.11.

Table 7.11: *Correlations between Year 3 task-switching and inhibition scores and Year 5 mathematics*

Measure	AMT	UA	CN	NF	CA	SH	ME	HD
Task-switching								
CC	.172	.263	.109	.168	.176	.156	.205	-.013
CNS	-.237	-.259	**-.406****	-.041	-.291	-.130	-.288	-.166
DCCS	.005	-.115	.015	-.030	.038	-.035	-.030	-.037
Inhibition								
WDW	-.048	-.046	.076	-.053	.100	-.109	-.014	-.040
VI	-.241	-.124	-.343	-.205	-.164	-.285	-.192	-0.313
MI	.151	.109	.145	-.020	.074	.213	.162	.138

CC = Creature Counting, CNS = Colour-number switch, DCCS = Dimensional card sort task, WDW = Walk / Don't Walk, VI = Verbal inhibition; MI = Motor inhibition, UA = using and applying mathematics, CN = counting and understanding number, NF = knowing and using number facts, CA = calculating, SH = understanding shape, ME = measuring, HD = handling data

** $p < .01$

7.6.7 Year 3 Predictors of Year 5 mathematics ability

No measures of inhibition and only one measure of task-switching were related to any of the Year 5 maths measures. This was possibly due to the factors that were discussed in Section 6.6; namely that inhibition consists of multiple processes that are not entirely captured by standard inhibition tasks (see Hasher et al., 2007); and that the task-switching measures used did not account for differences in preparation times between tasks (see Cepeda et al., 2001). Due to the absence of any robust relationships with Year 5 mathematics, inhibition and task-switching were excluded from further analyses. Similarly, as processing accuracy did not relate to Year 5 maths and recall time only related to one Year 5 sub-area component in a single CST, these performance indices were also removed from further analyses.

In Chapter Four and Chapter Five it was shown that the experimenter-led and computer-paced CSTs explained unique and shared variance in HLC; and that this may be explained by the importance of processing speeds in the computer-paced tasks and storage capacity in the experimenter-led tasks. To identify the predictors of overall task performance in the Year 5 mathematics, storage scores and processing times were entered into separate regression models for each CST, in each administration condition.

7.6.7.1 Year 3 Counting Span as a predictor of Year 5 mathematics ability

The first (i.e. experimenter-led) model accounted for 27.3% of the variance in Year 5 maths ability (R^2 = .27, p < .01) with storage demonstrating the only significant β value (β = .37, p < .05). The second (i.e. computer-paced) model accounted for 33.1% of the variance in Year 5 maths ability (R^2 = .33, p < .001) with processing time demonstrating the only significant β value (β = -.52, p < .01).

7.6.7.2 Year 3 Listening Span as a predictor of Year 5 mathematics ability

The first (i.e. experimenter-led) model was not significant (R^2 = .08, p = .12). The second (i.e. computer-paced) model accounted for 22.9% of the variance in Year 5 maths ability (R^2 = .23, p < .01) with storage demonstrating the only significant β value (β = -.46, p < .01).

7.6.7.3 Year 3 Odd One Out Span as a predictor of Year 5 mathematics ability

The first (i.e. experimenter-led) model accounted for 14.1% of the variance in Year 5 maths ability (R^2 = .14, p < .05) but neither storage nor processing times demonstrated significant β values. The second (i.e. computer-paced) model accounted for 22.5% of the variance in Year 5 maths ability ($R^2 = .26$, $p < .01$) with processing time demonstrating the only significant β value ($\beta = -.45$, $p < .01$).

7.7 Discussion

The current study investigated the relationship between measures of WM in Year 3 and mathematical ability in Year 5 using a novel measure of WM that accounts for individual differences in processing speeds within CSTs. Specifically, it was predicted that visuospatial and numerical WM capacity, as measured by Odd One Out Span scores, in seven- to eight-year-olds would predict mathematical ability two years later. Further, it was predicted that numerical and visuospatial processing times in seven- and eight-year-olds would account for unique variance in mathematical ability in nine- to ten-year-olds. Initial analysis showed that mathematics ability measured by Year 3 SATs performance related to all curricular components of mathematics assessed using a standardised mathematics test in Year 5. This indicated a consistency between the two measures with regard to assessment of ability.

With regard to WM storage capacity in Year 3, Counting Span scores correlated with Year 5 total maths score; however, contrary to the prediction, Span scores in Odd One Out Span did not related to Year 5 maths ability. Year 3 WM storage in Listening Span consistently related to all components of mathematics ability in Year 5. This finding contradicts studies that have found visuospatial WM, rather than phonological WM, to be related to mathematics ability in nine- and ten-year-olds (Alloway & Passolunghi, 2011; Holmes et al., 2008; McLean & Hitch, 1999). Alloway and Passolunghi found that visuospatial and phonological short-term memory predicted mathematical ability in seven-year-olds whereas visuospatial short-term memory alone predicted maths performance in eight-year-olds[7],

[7] Although visuospatial WM did not predict maths ability in the Alloway and Passolunghi study, it was argued that the considerable amount of variance shared between visuospatial short-term and working memory (i.e. 50%) indicated an over-lapping ability.

suggesting a key developmental change in seven- and eight-year-olds where phonological ability plays an important role in future mathematical learning, before the visuospatial ability takes over from approximately eight years of age (but see Holmes & Adams, 2006). Findings from the current study suggest that verbal WM storage ability (i.e. in Year 3) may be important in long-term learning (i.e. in Year 5), where the ability to store information in WM at approximately seven years of age provides a foundation of mathematical knowledge for future learning when visuospatial ability becomes more important. This is consistent with the findings of Gathercole and Adams (1994) who showed phonological WM capacity in five- and six-year-olds contributed significantly to long-term learning. However, further discussion of this finding is not possible without additional research investigation focused specifically on the link between WM and the learning trajectory. Therefore, this point is noted, but not included in subsequent discussion.

Processing times in Counting and Odd One Out Span correlated with Year 5 maths, yet links between Listening Span and Year 5 maths were not evident. This finding was expected, as speed of processing as a precursor to maths ability is well founded (Bull & Johnston, 1997; Geary et al., 2007; Li & Geary, 2013; Passolunghi & Lanfranchi, 2012; but see Anderson & Lyxell, 2007).

The regression models looking at the contributions from the individual CST mechanisms that showed significant correlations (i.e. storage, processing time) explained between 14% and 33% percent of variance in Year 5 mathematics ability. Specifically, visuospatial and numerical processing times predicted mathematics ability. This was consistent with the prediction that faster processing of visual stimuli is related to superior visuospatial ability, and this helps with ongoing mathematical learning (Li & Geary, 2013). The finding that processing time in the Counting Span task predicted maths was consistent with previous research that cites the importance of number fluency in arithmetic (Bull & Johnston, 1997; Hitch & McAuley, 1991; Swanson & Beebe-Frankenberger, 2004). Although some studies have argued that counting speed does not relate to mathematical ability (e.g. Passolunghi & Siegel, 2004), the processing time calculated in this study was recorded whilst memoranda were being stored (and possibly maintained in WM). Therefore, it was not a pure measure of processing speed, but a measure of WM processing speed.

Such findings indicate the benefit in looking beyond scores of storage in WM tasks in terms of relationships with HLC. For example, Holmes et al. (2008) used visual and spatial WM tasks (and a composite measure) to measure visuospatial ability in seven- to eight-year-olds and nine- to ten-year-olds, and recorded only correct recall as a measure of WM ability. It was found that the tasks could account for small, but significant, amounts of variance in maths ability (i.e. from 6% to 9%). It is unknown how the tasks would have related to maths ability had visuospatial WM processing speeds been considered, but the current study suggests that, whereas visuospatial *storage* scores alone accounted for very little variance in mathematics, visuospatial processing *times* within the WM tasks were strongly predictive of the ability.

As expected, results of the analysis into inhibition and mathematics found no links with Year 5 mathematics ability. Although there was one moderate correlation with task-switching (i.e. between CNS and the counting and understanding number component), overall, the results were consistent with previous research that has found no relationship with these executive abilities and mathematics in primary school children (Bull et al., 2008; van der Ven et al., 2012).

7.8 Executive summary

Longitudinal mathematical ability in primary school was predicted using both experimenter-led tasks, and computer-paced measures of WM that controlled for individual differences in processing speed. Consistent with predictions numerical WM storage capacity, and numerical and visuospatial processing speeds in Year 3 were predictive of maths ability in Year 5. Including processing times in the regression analyses enabled the identification of specific abilities that may be important in later mathematical learning. Identification of longitudinal predictors of mathematical ability is critical to early intervention programs (see Fuchs, Fuchs & Compton, 2012 for a review); and the current study has demonstrated that performance on WM tasks should not be limited to scores based on storage when considering the relationship with mathematics. Potential learning programs considering numerical WM storage ability and numerical and visuospatial processing speed are discussed in Chapter Eight.

8 Chapter Eight: General Discussion

8.1 Chapter Overview

This chapter provides a general discussion of the findings from all four empirical chapters in this thesis. Suggestions for practical applications, limitations of the thesis and future research opportunities are included.

This thesis examined the relationships between working memory (WM) and high-level cognition (HLC) in primary school children, including three complex span tasks (CSTs) to assess WM in both experimenter-led and computer-paced administration conditions. Extending other research that has examined the effect of temporal constraints on CSTs (Bailey, 2012; Barrouillet et al., 2009; Friedman & Miyake, 2004; Lépine et al., 2005; Lucidi et al., 2014; St Clair-Thompson, 2007), unique measures of WM were developed that took account of individual differences in processing speed on the processing component of each CST. The current work applied an experimentally derived time constraint that limited processing allowance proportionately according to each individual's processing speeds.

These CSTs also provided measures over and above the usual performance index of storage capacity, to include indices based on processing time, recall time and processing accuracy within the tasks. This allowed assessment of the relationship between HLC and each of these CST mechanisms. Measures of task-switching and inhibition were used to understand whether other key executive abilities accounted for further variance in HLC over and above contributions from the CST performance indices. A subsequent longitudinal study examined how each of the abilities assessed within the CSTs (i.e. storage, processing time, recall time, processing accuracy) and the two other executive abilities (task-switching, inhibition) in seven- and eight-year-olds predicted mathematical capability two years later, when they were nine and ten years old. The current chapter provides an overview of the results from the experimental chapters, with regard to the research aims of this thesis.

8.2 Summary of findings

Initial investigation found that the two CST administration conditions (i.e. experimenter-led, computer-paced) accounted for shared and unique variance in HLC, suggesting that the two task versions measured both different *and* similar cognitive abilities important in HLC. In order to understand the change in the WM-HLC relationship across conditions, task performance was investigated at a granular level. Examination of the underlying CST mechanisms (i.e. storage, processing time, recall time, processing accuracy) showed that, generally, processing time replaced storage ability as a predictor of HLC when time constraints were introduced. This was interpreted as highlighting a possible mediatory role for processing speed in the WM-HLC relationship.

However, WM involves cognitive activities beyond just processing and storing information, such as the coordination of resources (Baddeley, 1996) and attentional focus (Roome et al., 2014). Therefore, the executive abilities of task-switching and inhibition were examined to understand whether they explained further variance in HLC; and whether they related differently to tasks that were time-constrained compared to task that were not (i.e. thereby indicating a possible greater role in one condition compared to the other). It was found that measures of task-switching and inhibition did not relate to measures of WM span or HLC. However, rather than indicating that these skills did not contribute to the WM-HLC relationship, this was interpreted as indicative of the problematic nature of measuring executive abilities. This explanation was consistent with previous literature (e.g. van der ven et al., 2012) and relates to the issue of task-impurity (Burgess, 1997) and the possibility of these executive abilities representing a methodological artifact (van der Ven et al., 2012)

One major benefit of understanding how WM relates to HLC is the ability to predict performance on higher-order cognitive tasks such as mathematics. Furthermore, if it is possible to identify how deficits in WM relate to difficulties in academic performance, then intervention programs can be better targeted to address these deficits. Therefore, based on the understanding gleaned from the previous chapters, the longitudinal relationship between WM and mathematics was examined. It was found that numerical and visuospatial processing speeds, and numerical WM in seven- and eight-year-olds were important for mathematics ability two years later. This was consistent with previous literature that has looked at longitudinal predictors of maths ability in primary school children (Dummontheil & Klingberg, 2011; Li & Geary, 2014).

The studies in this thesis also examined whether the relationships between WM and HLC were domain-specific or domain-general. It was predicted that the numerical, verbal, and visuospatial WM tasks would relate to measures of HLC that are assumed to tap those same domains (e.g. verbal WM would relate to reading, numerical WM would relate to mathematics, etc.). However, it was found that numerical WM as measured by Counting Span was the single, best predictor of HLC alone, and when entered into a regression model with the other tasks. Also, Counting Span was relatively unaffected by administration condition compared to Listening and Odd One Out Spans. This was interpreted as partially supporting attentional models (e.g. Lépine et al., 2005; Lucidi et al., 2014), which posit that the use of simple processing stimuli (i.e. counting dots) in CSTs produces a purer measure of WM. This, it is argued, is because task performance is uncontaminated by individual differences in cognitive abilities that may be demanded by more complex stimuli such as reading sentences (Cowan et al., 2005; Lépine et al., 2005).

These findings supported the main hypothesis that CST administration condition would affect the relationship between WM and HLC and that this would be evident in the underlying mechanisms of the CSTs; however, the predictions of domain-specificity were not upheld. There were also further findings that require supplementary discussion. The following four sections discuss the outcomes from each empirical chapter. The implications from all findings for future research are discussed in Section 8.6.

8.2.1 A brief discussion of findings from Chapter Four

The aim of the first study (i.e. Chapter Four) was derived from existing research that has found time-restricted WM tasks, compared to tasks with no time constraints, to be more predictive of HLC in adults (Friedman & Miyake, 2004; St Clair-Thompson, 2007) and children (Lépine et al., 2005). However, the computer-paced WM tasks used in this thesis were designed to address a concern that existing studies had not considered individual differences in processing speeds when applying generic or mean (i.e. based on age) time constraints. Recent research has promoted the reliability of computer-paced WM tasks over experimenter-led tasks (Bailey, 2012; Lucidi et al., 2014), yet there was a gap in the literature with respect to understanding the differences between these two administration conditions in terms of what abilities they tap, and for considering individual differences in processing speed.

The current research was designed to understand how such individual differences might affect the relationship between WM and HLC. Based on the premise that computer-paced and experimenter-led tasks may tap both similar and different cognitive abilities, it was predicted that administration condition would affect the relationship between WM and HLC, and account for a combination of shared and unique variance in HLC, in seven- to eight-year-old children. Furthermore, the expectation was that there would be a degree of domain-specificity in the relationship between WM and HLC.

The findings from Chapter Four were, to a degree, in line with previous research that found time restrictions on CSTs increased the strength of their relationships with HLC (Friedman & Miyake, 2004; Lépine et al., 2005; St Clair-

Thompson, 2007). Using hierarchical multiple regression, it was demonstrated that storage accounted for variance in mathematics in only the computer-paced versions of Listening Span and Odd One Out Span. Also, when controlling for contributions from storage in the experimenter-led versions, both of these span tasks still predicted mathematics. However, when the computer-paced task was controlled for, the experimenter-led task did not predict maths ability. Consistent with other research (Bailey, 2012; Lucidi et al., 2014) using CSTs, Counting Span accounted for variance in mathematics in both administration conditions.

Furthermore, only the experimenter-led version of Counting Span accounted for unique variance in non-verbal reasoning over and above contributions from the computer-paced version. None of the computer-paced CSTs accounted for variance in reading ability when controlling for any variance accounted for (if any) by the experimenter-led version, and vice versa. When all CSTs were entered into the regression model together, Counting Span in the experimenter-led condition was the only measure to account for variance in non-verbal reasoning; and both versions of Counting Span were the only measures to predict mathematics ability.

Results did not suggest a domain specific relationship between WM and HLC, as there were no consistent relationships between CSTs and HLC measures with the same underlying domain (e.g. Listening Span and reading ability). As discussed, Counting Span consistently related to all measures of HLC, challenging research that has shown domain-specific links with HLC (e.g. Cain et al., 2004; Henry & Winfield, 2010), and supporting theories proposing a single attentional resource as the fundamental driver of WM capacity (Cowan et al., 2007).

With regard to shared and unique variance, it was found that 50% of the variance in HLC accounted for by Counting Span and Listening Span was shared between the two administration conditions (i.e. the computer-paced and experimenter-led versions). This was the case for non-verbal reasoning, reading and mathematics. Also, 25% of the variance accounted for in mathematics by Odd One out Span was shared between the computer-paced and experimenter-led versions. This supported the prediction that the two tasks versions tapped similar yet different cognitive abilities. These findings demonstrated that, when storage capacity was the only performance index used, the predictive relationships between WM (as measured by CSTs) and HLC varied depending on administration condition of the CST, and CST task type (i.e. numerical, verbal, visuospatial). To understand this finding further, the underlying mechanisms of the CSTs were examined in Chapter Five.

8.2.2 A brief discussion of findings from Chapter Five

Chapter Five addressed the reasons underlying why differences in the WM-HLC relationship appeared to be dependent on the administration condition of the CST. The analyses in Chapter Five suggested that an important factor contributing to these differing relationships related to which CST mechanism (i.e. storage, processing time, recall time, processing accuracy) was being assessed. For example, for Counting Span in the experimenter-led condition, storage predicted non-verbal reasoning and mathematical ability. However, investigation of the underlying CST mechanisms showed that in the computer-paced condition, processing time predicted non-verbal reasoning and mathematics with the β value for storage no longer significant. Also, Odd One Out Span only accounted for variance in HLC (i.e. mathematics) in the computer-paced condition, again with processing time providing the only significant β value. As paired *t*-tests showed that processing times were faster in the computer-paced versions of the tasks, this finding suggests that placing time restrictions on CSTs resulted in participants increasing their processing speeds, and that this effect was prevalent in children who achieved higher scores on measures of non-verbal reasoning and mathematics. This finding is discussed in greater detail in Section 8.3.3.

As discussed, previous research has found that time-restricted CSTs are more predictive of HLC than tasks with no time restrictions (e.g. Lépine et al., 2005). However, such research has used generic time restrictions, which may have disadvantaged children with slower processing speeds as they would not have had enough time to process the stimuli before moving to the storage/recall component of the task. This, in itself, could have altered the relationship with HLC. The current study used tasks that accounted for individual differences in processing speeds. In conjunction with performance indices based on the underlying mechanisms of the CSTs (i.e. storage, processing time, recall time, processing accuracy), titrated time restrictions meant it was possible to observe that changes in the WM-HLC relationship were not due to an unintentional disadvantage placed on children with slower processing speeds in a time-constrained condition, but were due to a change in performance in the underlying CST mechanisms, and their relationship with HLC. In order to assemble a comprehensive representation of the relationship between WM and HLC, it was important to examine contributions from other executive abilities; namely task-switching and inhibition. This was addressed in Chapter Six.

8.2.3 A brief discussion of findings from Chapter Six

Chapter Six addressed the varied findings from previous research into the relationships between HLC and measures of task-switching and inhibition (Bull & Scerif, 2001; St Clair-Thompson & Gathercole, 2006; van der Sluis, 2007; van der Ven et al., 2012). It was found that one task-switching measure (i.e. Creature Counting) accounted for additional variance in mathematics ability over and above contributions from the underlying CST mechanisms in Listening and Odd One Out Span. The fact that Creature Counting did not account for variance in mathematics over and above contributions from Counting Span suggests that it was the numerical (i.e. counting) element of the task that related to mathematics ability, and not the task-switching ability. Also, Creature Counting did not relate to reading or non-verbal reasoning ability (i.e. HLC measures not related to counting), which further supports this interpretation. Therefore, the overall findings from Chapter Six were consistent with those from existing research studies that have failed to find a strong link between HLC and measures of inhibition and task-switching (e.g. van der Sluis et al., 2007; van der Ven et al., 2012). Having explored a comprehensive model of the WM-HLC relationship, the benefits of the predictive nature of WM with regard to HLC were examined from a longitudinal perspective in Chapter Seven.

8.2.4 A brief discussion of findings from Chapter Seven

Given the consistent, strong relationship between WM and mathematics ability in the previous empirical chapters, Chapter Seven examined the longitudinal relationship between WM in Year 3 and mathematics ability in Year 5. When the storage scores and processing times were entered into a regression models (i.e. a separate model for each CST) it was found that Counting Span accounted for the variance in HLC in both administration conditions, with storage predicting maths in the experimenter-led condition, and processing time predicting maths in the computer-paced condition. Although the model for the experimenter-led Listening Span task was not significant, storage in the computer-paced version predicted mathematics performance. Odd One Out Span in both administration conditions predicted maths ability, but only the computer-paced version produced a significant beta value (i.e. for processing time).

These findings supported research that emphasises the importance of numerical and visuospatial WM in future early maths ability (Dummontheil & Klingsberg, 2011; Li & Geary, 2014). However, Listening Span predicted maths ability in the computer-paced condition, which was consistent with research showing the importance of verbal WM in future academic abilities (Gathercole & Adams, 1994).

8.3 Further discussion of key findings

Although discussions of the results from each study were included in the empirical chapters, there are **three** specific findings from the research as a whole that benefit from further examination here.

8.3.1 Unique and shared variance from each administration condition

In Chapter Four, it was found that the computer-paced and experimenter-led tasks accounted for unique and shared variance in HLC. This finding was similar to that of other studies that have sought to explain the reason for the influence of administration condition on the relationship between WM and higher-order cognitive abilities in adults (Bailey, 2012; Friedman & Miyake, 2004; St Clair-Thompson, 2007) and children (Lépine et al., 2005). However, as interpretations of these findings vary across studies, it is important to note that the tasks used in this thesis were able to make unique contributions to further understanding the effect of time restrictions on the relationship between CSTs and HLC.

A common interpretation of the finding that computer-paced tasks are more predictive of HLC than tasks that do not have time-constraints, is that the opportunity for strategy use in non-restricted tasks negatively affects the relationship with HLC (Lépine et al., 2005; Friedman & Miyake, 2004; St Clair-Thompson, 2007). The argument is that strategy use creates an increased cognitive load that has a detrimental effect on the WM-HLC relationship (Barrouillet et al., 2008; Cowan et al., 2007; Lépine et al., 2005; Lucidi et al., 2014); and that, therefore, if the opportunity for strategy is reduced, the relationship with HLC is stronger. This has been supported by investigations that have found processing times to be longer in unrestricted tasks, and that longer processing times were related to lower scores on measures of HLC (e.g. Lépine et al., 2005; St Clair-Thompson, 2007). Such studies have argued that strategy use is, therefore, unimportant in the WM-HLC relationship

When generic time constraints are used (as was the case with the studies referenced in the preceding paragraph), the participants with slower processing speeds are disadvantaged, and those with faster processing speeds are possibly unaffected. Therefore, the restrictions on strategy use are not consistent across the sample. The computer-paced tasks designed for measuring WM in this thesis avoided this issue by individually titrating the processing time allowance. It was found that time-constraints in the computer-paced condition did not result in a drop in storage scores, compared to the experimenter-led condition. However, processing speeds increased in the computer-paced condition, compared to the experimenter-led condition. These two findings may indicate that children increase their processing speeds in the computer-paced condition in order to allow enough time to maintain (e.g. rehearse) storage items. Therefore, while in the experimenter-led condition children were taking as much time as they needed to process the stimuli and still rehearse, when time restrictions were placed on the task some children were able to process the stimuli even faster in order to reserve some time at the end of processing to still apply maintenance strategies. Also, the children with faster processing speeds in the computer-paced tasks, tended to achieve higher HLC scores. Therefore, the reason for the difference in relationships with HLC between time-restricted and unrestricted CSTs may not be because time-restricted tasks reduce strategy opportunity, but because they identify those children who can increase their processing speeds and still use strategy to maintain memoranda.

However, as specific measures of strategy use were not used in the study in Chapter Five, it is still unclear whether or not strategy use in WM tasks can explain the relationship with HLC, and further exploration of this issue is not possible without research that specifically records and examines strategy use in both conditions. Such an approach has been undertaken by Friedman and Miyake (2004), but as their study did not use tasks that accounted for individual differences in processing speeds, interpretations are limited by the fact that participants with faster and slower processing speeds were differently (dis)advantaged. Suggestions for future research regarding this point are discussed in Section 8.6.7.

8.3.2 The comparative predictive strength of the WM tasks

In Chapters Four and Five, Counting Span consistently related to all measures of HLC in either the experimenter-led and computer-paced conditions (or both); whereas Listening Span and Odd One Out Span demonstrated weaker (and sometimes absent) relationships with HLC that were often dependent on administration condition. Therefore, it is important to ask the question: why was Counting Span strongly and consistently related to HLC, and why was it less affected by time constraints compared to other CSTs? As discussed in the previous section, findings from previous research have argued that allowing time for strategy use can impede WM performance and weaken the relationship with HLC. Researchers have posited that it is the attentional demand aspect of the CST that is responsible for the relationship with HLC, and that the increased cognitive load of maintenance (i.e. when allowed in unrestricted WM tasks) negatively affects this relationship (Barrouillet, et al., 2008; Cowan et al., 2007; Lépine et al., 2005; Lucidi et al., 2014). This could explain why storage (i.e. span score) in the computer-paced version of Listening Span was a better predictor of non-verbal reasoning and mathematics ability than the experimenter-led version, and why Odd One Out Span only predicted HLC in the computer-paced condition.

However, the fact that this finding was not as evident for Counting Span suggests that time restrictions did not disrupt the relationship with HLC for this task. Counting a small array of objects is an automatic and familiar procedure (Gallistel & Gelman, 1992), so the processing component of Counting Span, which consisted of simply counting a small display of dots, may have been too low to capture attention sufficient enough to disrupt maintenance, even when time was restricted in the computer-paced task. For Listening Span and Odd One Out Span, the processing stimuli, (i.e. sentences like; ‘Brothers are boys’, ‘Cars have four wheels’ in the former; and abstract shapes in the latter), were novel for the participant and, as discussed in Chapter One, novel stimuli require executive resources (Norman & Shallice, 1986). Therefore, the attentional demand for these two tasks may have been greater, and, therefore, more susceptible to the effects of time constraints.

In summary, the relationships between CSTs and HLC may have been relatively unaffected by administration condition when the attentional demands were low enough to withstand the additional time pressure (e.g., for Counting Span). This finding supports WM theories proposing that CSTs with elementary processing components are better measures of WM (Barrouillet et al., 2008), and are more predictive of HLC (Lépine et al, 2005) than tasks where the processing component is more complex.

8.3.3 Processing and storage in WM as predictors of HLC

The **third** key finding was that, generally, storage predicted HLC in the experimenter-led tasks, (i.e. when the regression model was significant), but processing time predicted HLC in the computer-paced condition[8]. Given that processing speed has been shown to be a mediator in the link between WM and HLC (see Fry & Hale, 2000 for a review), it is possible that this finding further connects processing speed to the WM-HLC relationship. Processing time predicted mathematics and non-verbal reasoning in the computer-paced version of Counting Span, but not in the experimenter-led condition. Similarly, Odd One Out Span only predicted mathematics in the computer-paced version, with processing time as the significant predictor.

The interpretation of these findings is that, although processing speed may mediate the relationship between WM and HLC, it is possible that this mediatory role

[8] Although these findings were not evident for any links between Listening Span and HLC, or WM and Reading, there is still value in discussing the relationships that Counting and Odd One Out Span showed with Non-verbal Reasoning and Mathematics.

was more influential when there was time pressure. The analysis in Chapter Five showed that processing times were linked to storage (i.e. evident in the negative correlations between processing times and storage for Counting and Odd One Out Span in both conditions), but was only linked to HLC when the WM tasks were time-restricted (i.e. evident in the negative correlations between processing times and non-verbal reasoning and mathematics in the computer-paced version of Odd One Out Span[9]). Therefore, this could be encapsulated as follows: (1) time restrictions in WM tasks led to an increase in processing speed; (2) this increase in processing speed was required to conserve WM storage items; (3) WM storage was related to HLC. When there were no time restrictions there was no requirement to increase processing speed to safeguard storage. Therefore, the link between processing time and HLC was not evident. This interpretation is consistent with the "cascade effect" described by Rose, Feldman and Jankowski, (2011, p. 1170) in their research into the effect of premature birth on processing speed, WM and HLC; and with conclusions reached in a review by Fry and Hale (1996; 2000) regarding a mediatory role for processing speed in the relationship between WM and HLC.

8.4 Practical applications

The predictive relationships between WM and mathematical ability two years later offer promising insights into mathematical teaching strategies for primary school children, and intervention programs for those children who struggle with mathematics learning. For example, a review by Mix and Cheng (2012) of the developmental literature regarding spatial ability and maths learning sought to identify opportunities for improving education techniques. It was found that, despite the well-established relationship between mathematics and visuospatial ability in children (Alloway &

[9] It is noted that processing time correlated with mathematics for Counting Span in the experimenter-led condition. However, the regression analyses showed processing time in the computer-paced condition to be a predictor of Mathematics.

Passolunghi, 2011; Dumontheil & Klingberg, 2012; Gathercole & Pickering, 2000; McLean & Hitch, 1999; van der Ven, et al., 2013; Li & Geary, 2013), explanations for this relationship were limited. Alloway and Passolunghi (2011) reported that visuospatial and verbal short-term memory predicted mathematics ability in seven-year-olds, but in eight-year-olds, maths ability was only predicted by visuospatial short-term memory. They suggested this finding was due to the development of a spatial mental representation of numbers. However, explanations were not provided regarding how this ability develops, and why it is useful. Furthermore, research has shown that certain WM domains (i.e. verbal, numerical, visuospatial) can be related to specific mathematical components. For example, van der Ven et al. (2013) found that visuospatial WM specifically related to addition and subtraction in younger children (i.e. six- to eight-year-olds), but this relationship was weaker in older children (i.e. eleven- to twelve-year-olds).

As discussed in Chapter Seven, storage and processing speed were found to predict mathematics differently dependent on task and administration condition. This further highlights the importance of understanding what each task type is actually measuring. Although research into WM and mathematics can provide insight into the key drivers of this ability, care should be taken in interpreting such findings too generally, as a broad application of the association between WM and maths learning may not be helpful when developing teaching programs for all aspects of mathematics at different ages. Such a position has been supported by the results of a survey by Gilmore and Cragg (2014), which found that teachers rated inhibition and shifting ability as important in maths learning, contrary to research demonstrating the primary influence of working memory storage capacity. The reason for this misbelief seemed to be due to teachers' exposure to research without being provided with complete explanations as to its application.

Some possible learning strategies are discussed based on the present findings and current research into the practical implications of WM in the classroom.

Gathercole and Alloway (2004) suggested the use of compensatory strategies to help children who struggle with the processing and storage demands of classroom learning. These mainly revolved around the same concept, which was to break down information into smaller components, thereby reducing the cognitive load of processing and storage. For example, if a child is prone to losing their place in a complex procedure, external memory aids, repetitive practice of individual steps and recognition of success within individual steps may help them in completing the task. It is useful to use the example of a mathematical procedure to demonstrate this. A typical example of a task used to measure data-handling ability in Year 3 is shown in Figure 8.1.

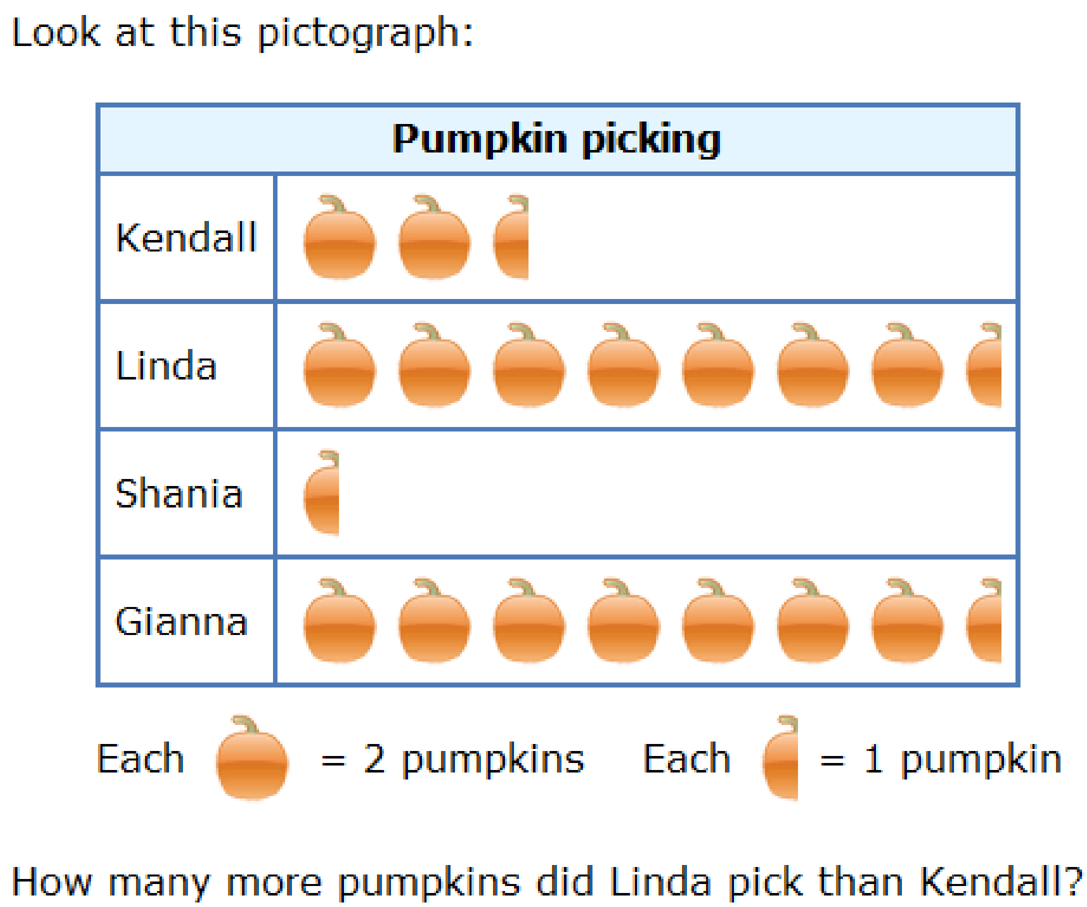


Figure 8.1. Example of a Year 3 data handling task (IXL Learning, 2015)

In order to calculate the correct answer for the problem in Figure 8.1, the child would typically go through the following steps:

1. Understand that half a pumpkin equals 1
2. Find Linda in the list
3. Add up all the whole and half pumpkins
4. Retain the number 15
5. Find Kendall in the list
6. Count how many pumpkins there are against that name
7. Remember that half a pumpkin equals 1
8. Retain the number 5
9. Know that 5 must be subtracted from 15 (i.e. not the other way around)
10. Subtract 5 from 15
11. Retain the number 10
12. Know that the result of that subtraction is the answer: 10

In addition, these steps must be carried out by either remembering the instructions or referring to the question in the text. Either way, a high cognitive load is apparent. From existing literature regarding WM in the classroom (e.g. Gathercole & Alloway, 2004) we know that a child who has WM deficits may repeatedly forget the question, forget their place whilst referring back to the question, experience delay in locating the information in the chart, and/or experience delay in counting the objects. In addition, they may have difficulty in performing the simple mental calculation. The challenges would be similar for a child struggling with mathematics in Year 5.

Making teachers aware of such challenges would enable the implementation of intervention solutions similar to those suggested by Gathercole and Alloway (2004). Walking the child through the steps they need to undertake may assist them in keeping their place in the task. Encouraging them to make physical notes (e.g. on paper or a whiteboard) regarding what information they have processed may reduce cognitive load (e.g. Linda = 15 pumpkins). Providing external memory aids for more complicated calculations (e.g. a chart showing counting up and down in '5's) may improve pace and thereby allow the child to stay on task.

The above example is quite specific; however the general understanding is that deficits in WM can create cognitive overload in children and result in learning impairment. Therefore, breaking down information and tasks into smaller steps can help reduce this load and allow incremental completion of tasks. The current research has demonstrated how components of WM contribute differently to certain abilities and that these can change dependent on the temporal demands of the task. Using this knowledge, it would be possible to develop programs that can help children develop strategies to complete classroom activities and achieve in school. In addition, recognised deficits can be overcome with the use of compensatory strategies in more efficient domains. For example, if numerical processing presents a challenge, the use of external visual memory aids may provide an alternative thereby reducing the numerical cognitive load. Should the deficit be in the visuospatial domain (e.g. mental representation of object location), verbal representation of the information (e.g. top, bottom, middle) could provide a supportive basis upon which to complete a task.

The current research has provided a tool that not only identifies deficits in specific WM mechanisms (i.e. storage, processing time, recall time, processing accuracy), and domains (i.e. numerical, verbal, visuospatial), but one that also demonstrates how these relate to HLC. Furthermore, with regard to mathematics ability, the final study shows that the relationship between WM and HLC changes as children progress through primary school, and therefore learning intervention programs may need to change accordingly.

8.5 Discussion of limitations

This thesis has extended existing research looking at the effects of temporal constraints on CSTs, and the relationship between WM and HLC in primary school children. Moreover, an investigation of the effect of time-restrictions on the underlying mechanisms of CSTs provided further insight into the WM-HLC relationship. However, some limitations are acknowledged. In addition to the loss of data due to the equipment malfunction mentioned in Chapter Three, **Six** further points are discussed.

8.5.1 Sample size

Challenges regarding the recruitment of schools and parental consent, coupled with a strict curriculum preventing unfettered access to children for testing somewhat limited participants numbers and assessment opportunities. It is acknowledged that a larger sample size would facilitate more robust analysis (e.g., structural equation modeling) to further investigate the WM-HLC relationship (e.g. path analysis regarding processing speed as a mediator for WM and HLC).

This limitation also had a further impact, as, had it been possible to recruit a large sample in the first year of data collection, larger numbers would have been available for the longitudinal study presented in Chapter Seven. Again, although the findings in the fourth study were informative, a larger cohort would have allowed for more robust analysis techniques.

8.5.2 Analytical methods

It was noted in Chapter Four (see Section 4.6) that the use of correlational analysis produced multiple significant values and that this was not surprising as, based on previous research, the relationship between HLC and across CSTs was expected. Furthermore, the correlations were used as an exploratory measure to ensure there were at least some relationships between the data to justify the used of multiple regressions. However, given the complexity of the interrelationships examined in this thesis, use of a more powerful experimental method (e.g. path analysis) would be beneficial. However, as noted in Section 8.5.1, the sample size required for such analytical methods was not possible within the confines of a three-year PhD.

8.5.3 Presentation of stimuli

It is important to note that, as discussed in Chapter Five, the method of stimuli presentation was inconsistent across WM tasks. For Counting and Odd One Out Span the stimuli remained available (i.e. on the computer screen) until the participant provided a response. However, for Listening Span, once the audio-delivery of the stimulus sentence was complete, it was no longer available. Therefore, it was possible that voluntary processing delays for purposes such as the refreshing or rehearsal of memoranda were more detrimental to performance on the Listening Span task, as the stimulus could be forgotten during the delay (see Towse et al., 2010). Therefore, for Listening Span, delays in processing may have had the opposite effect on storage (i.e. causing forgetting instead of aiding recall), and such an argument may explain why processing and storage were related in both versions of Counting and Odd One Out Span but in neither version of Listening Span. This issue in relation to task design may have affected the comparability of the measures. A Reading Span CST, with the sentence remaining in view for the entire duration of processing, may have been a more equivalent measure of verbal WM (Baddeley, Logie, Nimmo-Smith, & Brereton, 1985) alongside Counting and Odd One Out Span.

8.5.4 Measures of inhibition and task-switching

In Chapter One and Chapter Two of this thesis, different interpretations of how task-switching and inhibition can be measured (see Section 1.2.1.2 and Section 1.2.1.1), and how they relate to HLC (see Section 2.3) were discussed Also, in Chapter Six, a discussion was provided offering explanations as to why these measures failed to relate to each other and to HLC (see Section 6.6).

Two primary issues were raised; first, the task-impurity problem compromises accurate measurement of these executive abilities (Burgess, 1997); and, second the cognitive function these constructs represent can be interpreted in different ways, and therefore are measured by tasks that partially overlap in the abilities they tap (Miyake et al. 2000; Miyake & Friedman, 2012). Attempts to measure inhibition and task-switching at a latent variable level in this thesis were not successful, and this was possibly due to the two issues raised here. In particular, the DCCS task did not relate to any other executive measures, or with HLC. This was surprising given its popularity in the literature[10].

As well as the explanations provided in Chapter 6 for the general lack of correlations between the executive ability tasks, it is noted here that more precise choices of task may have been more suitable. For example, the DCCS may not have been age-appropriate for the sample (even though the border version was used as recommended by Zelazo, 2007). Alternatively, the issue of cognitive salience (Towse et al., 2000a; discussed in Section 1.2.1.2) may have affected its relationship with the other tasks that may be more representative of mental flexibility (see Section 1.2.1.2 for more detail on this point). The Walk/Don't Walk task could be more representative of an ability to interrupt a response rather inhibit a prepotent one, as is more likely the case with the VIMI task (Verbruggen & Logan, 2008). These are all possibilities that could have affected the results in Chapter Six and Chapter Seven, and it is acknowledged that selection of a set of more comparable tasks may have produced different results (notwithstanding the task-impurity and unity/diversity issues discussed in Chapter Six).

[10] It is noted that Zelazo (2006) argues that the DCCS is an embedded-rule task and not a measure of task-switching; however the DCCS has been used extensively as a measure of task-switching in the literature regarding executive function in children. This point is discussed in detail in section 1.2.1.2)

8.5.5 Standardised mathematics test

With regard to the mathematics assessment in Year 3, it would have been preferable to use a standardised task (i.e. a parallel form of the Access Mathematics Test, McCarty, 2008) that addressed the subcomponents of the UK curriculum. Unfortunately, a mix of private and state sector schools resulted in variation in Year 3 curriculum with the private school having more flexibility with regard to teaching content. It would have been preferable to recruit all participants from the state school system and thereby have a consistent curriculum base upon which to assess the children.

8.5.6 Socioeconomic status

The recruitment of a private school possibly created a skewed influence of socioeconomic status (SES) in favour of those children from more privileged social and economic backgrounds. . Although SES has been shown not to influence WM and executive abilities in children (Engel, Santos & Gathercole, 2008; Wiebe, Espy & Charak, 2008; but see Diamond, 2001), other research has shown detrimental effects on mathematical ability for children in lower SES groups (e.g. Krajewski & Schneider, 2009). Variation in SES cannot be avoided, but it would have been informative to include a measure of SES in the study.

8.6. Future directions

Although findings from this thesis do not *definitively* support theories citing the importance of processing speed (Case, 1995), retention duration (Towse et al., 1998), strategy use (Baddeley et al., 1975) or attention without strategy use (Lépine et al., 2005), they do support the notion that processing times (and the possible allowance of strategy use as a result) play a role in WM. There are areas of investigation that can further contribute to an understanding of the underpinnings of

CST performance, and how WM relates to HLC. Therefore, contributions from this thesis to existing theory and suggestions for future research are discussed here.

8.6.1. The role of maintenance strategies

Previous research with adults has used participant interviews to identify what strategies (if any) were used in CSTs using generic time restrictions, compared to when the tasks were participant led (Friedman & Miyake, 2004). Although it was found that there were strategy differences between the two conditions, this did not explain differences in the relationships between CST performance and HLC. The computer-paced tasks designed for this thesis were able to place a more precise restraint on processing time (i.e. allowing just enough time for processing at an individual level for all participants) compared to CSTs with a generic time-constraint. Therefore, it is possible that use of such tasks could result in greater differences in strategy use when compared to the experimenter-led tasks, as the possibility of participants with faster processing speeds receiving an advantage (i.e. extra time for strategy use) is reduced (see Section 2.5 for a discussion of this issue). A comparison of performance on CSTs in the two administration conditions, in conjunction with strategy interviews may provide further insight into qualitative differences in CST performance.

In addition, a comparison of experimenter-led and computer-paced tasks with the additional manipulation of blocking rehearsal would assess whether or not such strategy use was important in either condition. Methods such as articulatory suppression (i.e. continuous repetition of a simple word such as “baba”) have been shown to reduce memory performance due to the prevention of sub-vocal rehearsal (Baddeley, 1986). Should articulatory suppression reduce span scores in the experimenter-led condition but not in the computer-paced condition, this could indicate a key qualitative difference in performance in each CST version. For example, strategy use may aid performance when tasks are not time-constrained, but when this is not possible processing speeds could be increased to prevent decay. This would be partially supportive of the resource-sharing hypothesis (Case et al., 1982), as it would indicate a degree of fluidity in resources dependent on task demand. However, should articulatory suppression decrease performance in both conditions, this may indicate that participants increase their speed when necessary in order to implement maintenance strategies. This would support the notion of an intermediary role of processing speed in WM and HLC (Fry & Hale, 1996).

With a greater understanding into the effect of time constraints with regard to strategy use, it would be possible to assess different models of WM and the relationship with HLC. As discussed, the TBRS model (Lépine et al., 2005) and unitary theory (Cowan et al., 2007) argue that strategy is unimportant in the WM-HLC relationship as only the attentional resource is important in determining this link. Therefore, a lack of strategy use in the time restricted condition, which in turn holds stronger links with HLC would support this argument. However, should strategy use still be in play when times are restricted, this would support the view that maintenance strategies are important drivers for WM capacity (Baddeley & Hitch, 1974; Henry et al., 2008; Logie, 2003) and their link with HLC (Baddeley, 1990).

8.6.2. The role of interference

The finding that faster processing times correlated with greater storage capacity in both conditions (see Section 5.5.4) is consistent with previous studies (e.g. Kail, 2000). However, evidence that slower processing times in the experimenter-led condition did not decrease storage capacity (see Section 4.5.1) challenges the notion that longer retention durations lead to decay (Towse & Hitch, 1995), or reduce temporary storage space (Case, 1995). An alternative view is that faster processing speeds reduce interference (Zacks & Hasher, 1988), and therefore prevent loss of memoranda (Barrouillet et al., 2004). If this ability were important in HLC, as Hasher and colleagues would argue (e.g. Lustig, May & Hasher, 2001), this would explain the stronger relationships with HLC in the computer-paced verbal and visuospatial tasks.

The use of interpolated tasks (Towse et al, 1998; 2002) in both the experimenter-led and computer-paced conditions could determine whether interference is greater when retention durations are longer. Should interference play an important role in CST performance then it could be expected that the interpolated task would have a more detrimental effect on span score when there is more time (i.e. in the experimenter-led condition) for the products of processing from distractor tasks to become incorporated into WM (Hasher, Stolzfus, Zacks & Rypma, 1991). Such a finding would provide evidence for the role on interference in the WM.

8.6.3. Research with adults

Towse et al. (1998) have argued that retention time, rather than processing speed is what underpins storage performance in WM with the former dictating likelihood of decay in children. Similarly, in a study with adults, Towse et al. (2000) found that WM span was unrelated to processing time, although retention duration did affect storage. This was consistent with findings from other studies with adults (e.g. Engle et al. 1992; but see Friedman & Miyake, 2004). Results from Towse et al. (2000) mirrored the pattern of WM performance in children (Towse et al., 1998) for all but the correlation between processing times and storage scores. Therefore, Towse et al (2000) suggested that, in line with Towse et al. (1998), it is “forgetting over time” (p.18) that affects WM span. However, it was also argued that such findings do not fully explain the task-switching model (Towse & Hitch, 1995) and that investigation into the mechanisms underlying CST performance are required.

The methodology used in the current thesis could be applied to adults in order to build on findings from Towse et al. (2000). In Chapter Five, processing times played an important role in CST performance when times were restricted, partially supporting the view that retention duration influences span scores. However, the difference between adults and children is that processing times do not correlate with span scores for the former (Towse et al., 2000), whereas the studies in this thesis show that they do for the latter (see Chapter Five). The manipulation of processing times and granular analysis of performance afforded by the tasks used in this thesis may provide further insight into the mechanisms of WM in adults. For example, when adults are forced to perform CSTs based on their individual processing speeds (as they would in the computer-paced condition), the relationship between processing times and storage may be more evident, and therefore provide further support for the task-switching hypothesis (Towse & Hitch, 1995).

8.6.4. Intervention research

An understanding of the practical application of the findings in the current research would be beneficial, as such insight would be relevant to the development of intervention programmes. It is recommended that future studies develop and implement learning interventions based on the current findings for comparison with existing programmes. There is research evidence to suggest the effectiveness of targeting WM abilities using training interventions, to both improve WM and other cognitive skills such as mathematics ability in children (Holmes et al., 2009; Kroesbergen, van ‘t Noordende & Kolkman, 2014). Although it is noted that the generalisability of gains in WM following WM training, to HLC generally, and to educational attainment specifically, has also been shown to be limited (see Melby-Lervag & Hulme, 2013 for a meta-analysis of the literature). Despite this, there is considerable evidence that the development of compensatory strategies may be effective (Holmes, Gathercole & Dunning, 2009; Henry & Winfield, 2010).

8.7. Summary and conclusion

The principal aim of this thesis was to further explain the relationship between WM and HLC in children. Performance on computer-paced tasks was compared to performance on tasks that did not restrict administration time (i.e. experimenter-led), and a pattern of shared and unique variance in HLC was accounted for by the tasks in the two conditions. Assessment of storage, processing time, recall time and processing accuracy indicated that, generally, processing time replaced storage as a predictor when time constraints were introduced. At a time when recommendations are being made to use computer-paced measures of WM instead of self-paced and experimenter-paced tasks (e.g. Bailey, 2012; Lucidi et al., 2014), such findings provide an understanding of how these restrictions affect the relationship with HLC. Therefore, researchers need to be aware of the complexities of CSTs, and the effect of administration conditions, when considering their relationships with HLC.

With regard to WM theory, findings from this thesis have offered support and challenges to the main models of WM. The link between faster processing times and higher span scores supported the TBRS model (Barrouillet & Camos, 2001), as faster processing is said to provide micro-switching opportunities that result in increased storage. This positive relationship between processing speed and storage capacity also supported both the task-switching hypothesis (Towse & Hitch, 1995; Towse et al., 1998), which argues that faster processing leads to more prompt recall, thereby reducing decay; and the resource-sharing hypothesis (Case et al., 1982) which posits that more efficient processing allows more cognitive resources to be used for storage.

However, the finding that individually titrated processing times did not impair storage is contrary to the TBRS model that argues that time restrictions prevent micro-switching resulting in reduced span scores (Barrouillet et al., 2009). As processing times significantly increased in the computer-paced condition, it is possible that maintenance strategies (e.g. micro-switching) were still utilised to refresh memoranda. This could indicate a degree of fluidity in WM resources, with task demand dictating when each of these cognitive resources (i.e. processing or storage) is required to differing degrees. As discussed in Section 8.5.7, this possibility is worthy of further investigation.

With regard to domain-specific and domain-general accounts of WM, there was little evidence of domain-specific links between WM and HLC, with no strong relationships seen between CSTs and HLC measures with the same underlying domain (e.g. Listening Span and reading ability). In fact, Counting Span consistently related to all measures of HLC. This challenged the multi-component model of WM that posits domain-specific stores of information in WM (Baddeley & Hitch, 1974); and research that has shown domain-specific links with HLC (e.g. Cain et al., 2004). Conversely, it supported theories that propose a domain-general attentional resource as the fundamental link between WM and HLC (Cowan et al., 2007; Lépine et al., 2005). However, Lépine et al. argued that time constraints produced stronger links with HLC due to the reduction of strategy opportunity. Yet, the finding that relationships between Counting Span and HLC were relatively unaffected by time restrictions contradicts this argument.

Generally, this thesis has provided evidence for a fluid interplay between storage and processing in WM in children, driven by individual differences in processing efficiency. This suggests that WM is representative of more than the ability to process information in the presence of a concurrent memory load. Further research into the underlying elements that are involved in WM task performance is required to understand this capacity that is important in HLC (see Section 8.6).

As well as offering further insight into what CSTs measure in children, the intention is that these findings will provide a foundation upon which learning intervention programs can be built. Ultimately, it is hoped that effective support can be offered to those children who, due to WM deficits, struggle with learning throughout the primary school years.

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Appendix A: Consent Information Sheets and Forms

1) School Invitation and Consent form

London South Bank University

School of Psychology, Borough Road, London, SE1 0AA

University Research Ethics Committee

Invitation to Participate in a Research Study

Study Title

Individual Differences in Working Memory Function and High-level Cognition in Primary School Children

Dear *<insert Head Teacher's name>*

Your school is being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please contact me by any of the methods given at the end of this document if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish your school to take part. Thank you for taking the time to read this.

Rebecca Gordon

London South Bank University

What is the purpose of the study?

This study will be looking at how children perform on tasks relating to skills such as attention, memory, and mathematics. If you agree to take part, your students will be asked to take a series of short tests to see how they solve problems.

Do the students have to take part?

It is each parent/guardian's decision as to whether their child participates in this study. If you do decide to allow your school to take part, you will be given this information sheet to keep and be asked to sign the consent form below. Each parent/guardian will then be given an information sheet, invitation and consent form. This can be taken home by each child, and given to their parent/guardian when the study commences in September 2012. Should you wish for me to provide information to the parents in the form of an information evening, this can also be arranged at the school's convenience. Should the parent/guardian decide to allow their child to participate, they will be asked to sign the consent form and return it to the school. The information sheet is to be kept by them for their records.

The study is not expected to make any child feel uncomfortable or to upset them in any way. They can stop taking part in the study at any time. They can do this up to 3 months after the end of the study, or at any point before the results are used in publication of the study. Please note, any child's name or anything else which could let people know who they are, will not be used in any way in any publications of study.

What will the children be asked to do?

Each child will be asked to perform a series of short tasks which are designed to be fun and engaging for children. These are all conducted on a one to one basis with the researcher and will take place over 3 sessions of 40 minutes each. In addition, there will be 3 short mathematics tests and an IQ test. These will be conducted in 2 group sessions, taking up to approximately 45 minutes each.

The group sessions can be conducted in the classroom. However, a private space on school premises, free of distractions, will be required for the one to one sessions.

Will the children's participation be kept confidential?

All information which is collected about each child during the course of the research will be kept strictly confidential. Any information about a child which is shared with others (for example, as part of a published study or with the study's supervisor) will have the child's name and any identifying information removed so that they cannot be recognised from it.

The data will be stored securely on the researcher's computer, and also on a password protected backup disc.

When the study is finished, the data will be securely kept for a period of 5-7 years post publication information. Data will only be presented in summary form and not for each individual child.

What will happen to the results of the study?

It is anticipated that the results of this study be written up for publication in 2014. As yet, it is not know what form the publication will take but the intent is for publication in a psychology journal. No child will be identified in the publication of the findings of this study, as data will only be presented in summary form, and not for individual children.

Who has reviewed the study?

This research is sponsored by London South Bank University and, as such, the University Research Ethics Committee has reviewed and approved this study.

Contact for further information.

Should you have any queries about the study at any stage please contact me, as lead researcher, using the details given below. Should you wish to make a complaint regarding the study, please contact my supervisor using the details given below. Should you be unable to resolve any complaint with the research team, you can contact the Chair of the University Research Committee using the details given below.

Lead Researcher

Rebecca Gordon

Doctoral Researcher

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Chair of Ethics Committee

University Research Ethics Committee

London South Bank University

Telephone: +44 (0) 20 7815 6095

Consent Form

Individual Differences in Working Memory Function and High-level Cognition in Primary School Children

I have read the attached information sheet on the research in which I have been asked to allow my school to participate. I have also been given a copy to keep. I have had the opportunity to discuss the details and ask questions about this information.

The investigator has explained the nature and purpose of the research and I believe that I understand what is being proposed.

I understand that my school's involvement and any data from this study will remain strictly confidential.

I have been informed about what the data collected in this investigation will be used for, to whom it may be disclosed, and how long it will be retained.

I understand that I am free to withdraw the school from the study at any time, without giving a reason for withdrawing. I understand that any child is free to withdraw from the study at any time, without giving a reason for withdrawing. Similarly, I understand that any parent/guardian is free to withdraw their child from the study at any time, without giving a reason for withdrawing.

I hereby fully and freely consent to my school's participation in this study.

School Name: ……………………………………

Head Teacher's Name: …………………………………..

Date: ……/………/…………

As the investigator responsible for this investigation I confirm that I have explained to the individual named above the nature and purpose of the research to be undertaken.

Investigator's Name: …………………………………..

Investigator's Signature: …………………………………..

Date: ……/………/…………**1)**

2) Parent Invitation and Consent form

London South Bank University

School of Psychology, Borough Road, London, SE1 0AA

University Research Ethics Committee

Invitation to Participate in a Research Study

Study Title

Individual Differences in Working Memory Function and High-level Cognition in Primary School Children

Dear parent/guardian

You are being invited to allow your child to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please contact me by any of the methods given at the end of this document if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish your child to take part. Thank you for taking the time to read this.

Rebecca Gordon

London South Bank University

What is the purpose of the study?

This study will be looking at how children perform on tasks relating to skills such as attention, memory, and mathematics. If you agree to take part, your child will be asked to take a series of short tests to see how they solve problems.

Why has my child been chosen?

The head teacher of your child's school has agreed to participate in this study. Therefore, it is the intention that all the children in your child's year participate. To this end, I am contacting the parent or guardian of each child to seek consent for them to participate.

Does my child have to take part?

It is your decision as to whether your child participates in this study. If you do decide to allow your child to take part, you will be given this information sheet to keep and be asked to sign the consent form on the attached sheet. Two copies have been provided, so that you may keep one for your own records.

The study is not expected to make your child feel uncomfortable or to upset them in any way. They can stop taking part in the study at any time.

If you want to stop your child from taking part, you do not have to give a reason and it will not affect you or your child in anyway. If you chose to stop taking part, you can contact the researcher, stating an ID number given to you at the start of the study. You can do this up to 3 months after the end of the study, or at any point before your results are used in publication of the study. Please note, your child's name or anything else which could let people know who they are, will not be used in any way in any publications of study.

What will my child be asked to do?

All testing will take part in the school either in the classroom (for group sessions) or in a designated quiet room (for one to one sessions). Your child will be asked to perform a series of short tasks which are designed to be fun and engaging for children. These are all conducted on a one to one basis with the researcher and which will take place over 3 sessions of 40 minutes each. In addition, there will be 3 short mathematics tests and an IQ test. These will be conducted in 2 group sessions, taking approximately 45 minutes each.

Will my child's participation be kept confidential?

All information collected about your child during the course of the research will be kept strictly confidential. Any information about your child which is shared with others (for example, as part of a published study or with the study's supervisor) will have your child's name and any identifying information removed so that they cannot be recognised from it.

The data will be stored securely on the researcher's computer, and also on a password protected backup disc.

When the study is finished, the data will be securely kept for a period of 5-7 years post publication information. Data will only be presented in summary form and not for each individual child.

What will happen to the results of the study?

It is anticipated that the results of this study be written up for publication in 2014. As yet, it is not know what form the publication will take but the intent is for publication in a psychology journal. No child will be identified in the publication of the findings of this study, as data will only be presented in summary form, and not for individual children.

Who has reviewed the study?

This research is sponsored by London South Bank University and, as such, the University Research Ethics Committee has reviewed and approved this study.

Contact for further information.

Should you have any queries about the study at any stage please contact me, as lead researcher, using the details given below. Should you wish to make a complaint regarding the study, please contact my supervisor using the details given below. Should you be unable to resolve any complaint with the research team, you can contact the Chair of the University Research Committee using the details given below.

Lead Researcher

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Doctoral Researcher

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Consent Form

Individual Differences in Working Memory Function and High-level Cognition in Primary School Children

I have read the attached information sheet on the research in which I have been asked to allow my child to participate. I have also been given a copy to keep. I have had the opportunity to discuss the details and ask questions about this information. The investigator has explained the nature and purpose of the research and I believe that I understand what is being proposed.

I understand that my child's involvement and my child's data from this study will remain strictly confidential.

I have been informed about what the data collected in this investigation will be used for, to whom it may be disclosed, and how long it will be retained.

I understand that my child is free to withdraw from the study at any time, without giving a reason for withdrawing. Similarly, I understand that I am free to withdraw my child from the study at any time, without giving a reason for withdrawing.

I hereby fully and freely consent to my child's participation in this study.

Child's name: ……………………………………

Parent/Guardian's Name: ……………………………………

Parent/Guardian's Signature: …………………………………...

Date: ……/………/…………

As the investigator responsible for this investigation I confirm that I have explained to the participant's parent/guardian named above the nature and purpose of the research to be undertaken.

Investigator's Name: …………………………………...

Investigator's Signature: …………………………………...

Date: ……/………/…………

Copy to keep

Consent Form

Individual Differences in Executive Function and Mathematical Ability in Primary School Children: A latent variable analysis.

I have read the attached information sheet on the research in which I have been asked to allow my child to participate. I have also been given a copy to keep. I have had the opportunity to discuss the details and ask questions about this information. The investigator has explained the nature and purpose of the research and I believe that I understand what is being proposed.

I understand that my child's involvement and my child's data from this study will remain strictly confidential.

I have been informed about what the data collected in this investigation will be used for, to whom it may be disclosed, and how long it will be retained.

I understand that my child is free to withdraw from the study at any time, without giving a reason for withdrawing. Similarly, I understand that I am free to withdraw my child from the study at any time, without giving a reason for withdrawing.

I hereby fully and freely consent to my child's participation in this study.

Child's name: ……………………………………

Parent/Guardian's Name: ……………………………………

Parent/Guardian's Signature: …………………………………...

Date: ……/………/…………

As the investigator responsible for this investigation I confirm that I have explained to the participant's parent/guardian named above the nature and purpose of the research to be undertaken.

Investigator's Name: …………………………………...

Investigator's Signature: …………………………………...

Date: ……/………/…………

3) Script for child consent

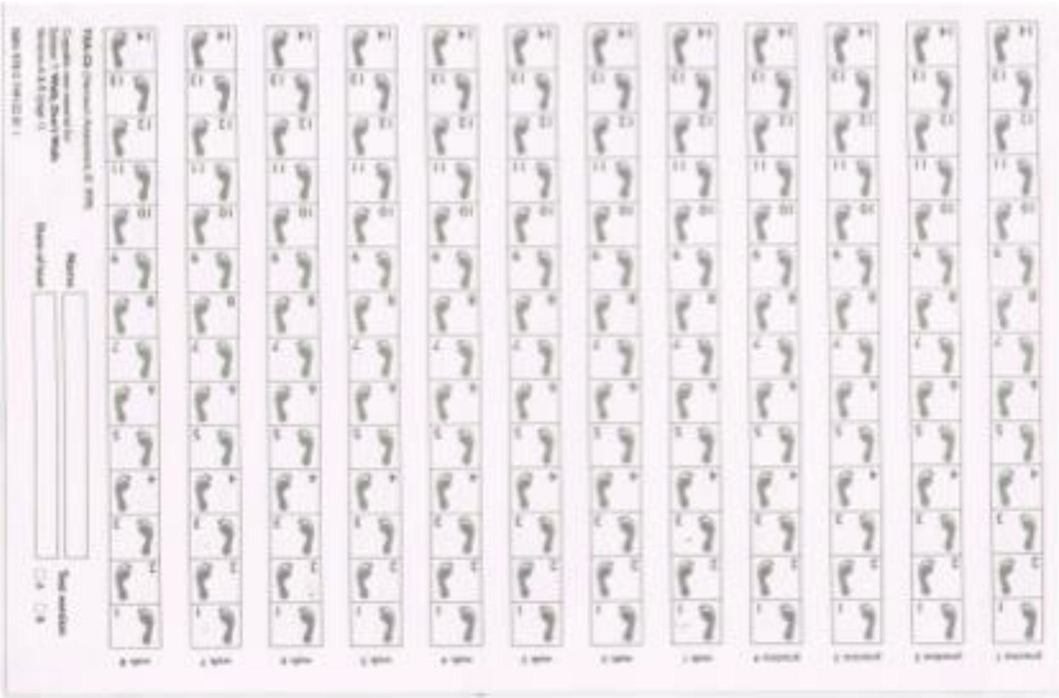
‘I am a researcher and I interested in finding out how children your age pay attention and remember things. Your mummy or daddy, or the person who looks after you has agreed for you to do some tasks with me, which will help me find out more about how you pay attention and remember things. If you don’t want to do these tasks, you don’t have to. You can ask that we stop at anytime, and that’s ok. I am now going to ask you whether or not you want to do these tasks with me, but I need to record it. So I am going to ask you “<name>, would you like to do some tasks with me?” and, if you are happy to do the tasks, I want you to say “yes”; but if you are not happy for me to do the tasks, I want you to say “no”. Are you ready?’

If the child understands and is ready to give (or not give) consent, then:

‘I am here with <full name>. <Full name> would you like to do some tasks with me?’.

The child’s response was then recorded. Only a response of yes permitted the continuation of testing.

Appendix B: Walk / Don't Walk Record Sheet



Appendix C: Verbal Inhibition Motor Inhibition Score Sheet

Number' ' ' '

Name' ' ' ' '

Date' ' ' ' '

''

Response'Sheet'for'Conflicting'Motor/Verbal'Response'Task'(VIMI)'

Motor'Task''

Palm/Fist*

*	Copy' 1'	Response'	Inhibit' 1'	Response'	Copy' 2'	Response'	Inhibit' 2'	Response'
1*	A*	*	B*	*	B*	*	A*	*
2*	A*	*	A*	*	B*	*	B*	*
3*	B*	*	B*	*	A*	*	B*	*
4*	B*	*	A*	*	A*	*	A*	*
5*	A*	*	A*	*	B*	*	B*	*
6*	B*	*	A*	*	A*	*	B*	*
7*	A*	*	B*	*	B*	*	A*	*
8*	B*	*	B*	*	A*	*	A*	*
9*	A*	*	A*	*	A*	*	B*	*
10*	B*	*	B*	*	A*****	*	A*	*
11*	B*	*	A*	*	B*	*	B*	*
12*	A*	*	B*	*	B*	*	A*	*
13*	B*	*	A*	*	A*	*	A*	*
14*	B*	*	B*	*	B*	*	A*	*
15*	A*	*	B*	*	A*	*	B*	*
16*	A*	*	A*	*	B*	*	B*	*
17*	B*	*	B*	*	A*	*	A*	*
18*	A*	*	B*	*	B*	*	B*	*
19*	B*	*	A*	*	B*	*	A*	*
20*	A*	*	A*	*	A*	*	B*	*
*	Time* * *	Errors*	Time*	Errors*	Time*	Errors*	Time*	Errors*

Total*Time:*********************Total*Errors:*

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Verbal'Task''

Day/Night*

*	Copy* 1*	Response*	Inhibit* 1*	Response*	Copy* 2*	Response*	Inhibit* 2*	Response*
1*	A*	*	B*	*	B*	*	A*	*
2*	A*	*	A*	*	B*	*	B*	*
3*	B*	*	B*	*	A*	*	B*	*
4*	B*	*	A*	*	A*	*	A*	*
5*	A*	*	A*	*	B*	*	B*	*
6*	B*	*	A*	*	A*	*	B*	*
7*	A*	*	B*	*	B*	*	A*	*
8*	B*	*	B*	*	A*	*	A*	*
9*	A*	*	A*	*	A*	*	B*	*
10*	B*	*	B*	*	A*	*	A*	*
11*	B*	*	A*	*	B*	*	B*	*
12*	A*	*	B*	*	B*	*	A*	*
13*	B*	*	A*	*	A*	*	A*	*
14*	B*	*	B*	*	B*	*	A*	*
15*	A*	*	B*	*	A*	*	B*	*
16*	A*	*	A*	*	B*	*	B*	*
17*	B*	*	B*	*	A*	*	A*	*
18*	A*	*	B*	*	B*	*	B*	*
19*	B*	*	A*	*	B*	*	A*	*
20*	A*	*	A*	*	A*	*	B*	*
*	Time* * *	Errors* *	Time*	Errors*	Time*	Errors*	Time*	Errors*

Total*Time:****************************Total*Errors:*

'

'

Appendix D: Data exploration procedures and scoring rationale for task-switching and inhibition measures

Motor inhibition

Initial exploration was conducted on total errors for the motor inhibition task as this had previously been demonstrated as the most robust scoring method (Henry et al., 2012). A positive skew with high score outliers was found and the test of normality was significant ($p < .001$). Therefore, the following steps were taken to normalize the data. Initially, a single high-score outlier was trimmed, however, a significant test of normality ($p < .001$) remained. The removal of a further four high-score outliers were then removed but the test of normality was still significant ($p <.001$) The original full set of data were then transformed to z-scores to identify any outliers greater than 2.5.standard deviations from the mean. Three high scores were identified and winsorized by substitution with the preceding highest score. However, a positive skew with a significant test of normality ($p <.001$) was still evident. A log transformation was performed on the full data set with no reflection (i.e. due to the positive skewness). As there were some zero values but no negative values, a +1 adjustment was added to each case. As a result, the test of normality was not significant ($p =.128$, skewness = -.149, kurtosis = -.287). Based on this exploration procedure, it was decided that the motor inhibition score be calculated as the sum of total errors with a log transformation including an adjustment of +1. This ensured no significant test of normality and acceptable ranges of skewness and kurtosis (George & Mallery, 2010).

Verbal Inhibition

Initial exploration was conducted on total errors as this had previously been shown to be the most robust scoring method (Henry, et al., 2012). This showed a positive skew with high score outliers. The test of normality was significant ($p < .001$). As more than 50% of the sample had zero errors, it was decided that a time cost analysis should be undertaken. Exploration on total time showed a positive skew with high score outliers. The test of normality was significant ($p < .001$). Therefore the following steps were undertaken to normalize the data. Two high-score outliers were identified and trimmed, resulting in a slight positive skew and a significant test of normality ($p < .001$). The data were then converted to z-scores that did not identify any outliers greater that 2.5 standard deviations from the mean. As such, winsorizing was not performed. As the original data were positively skewed, a log transformation was performed with no reflection. Due to the presence of some zero values and negative values, an adjustment of the lowest score plus .01 was added to each case. This resulted in a large negative skew and a significant test of normality ($p < .001$, skewness = -4.28, kurtosis = 29.45). A square root transformation was then performed on the original data. To eliminate negative values, an adjustment of the lowest score was added to each case. This resulted in a test of normality that was very close to non-significance ($p = .048$, skewness = .27, kurtosis = 1.61). Based on the result of the log transformation, it was decided that this method (i.e. including an adjustment of the lowest score added to each case) be used to calculate the verbal inhibition score.

Walk / Don't Walk

For the Walk / Don't Walk (WDW) measure, initial exploration was conducted on the number of total trials correct as advised by the task administration manual from The Test of Everyday Attention for Children (TEA-Ch; Manly, et al., 2001). This showed a slight positive skew with high score outliers. The test of normality was significant ($p = .008$). Therefore, the following steps were taken to normalize the distribution. A single high-score outlier was identified and trimmed from the data. This resulted in a significant test of normality ($p < .05$). The data were then converted to z-scores and a single high-score was identified as further than 2.5 standard deviations from the mean. This was then winsorized by substitution with the preceding highest score. However, the test of normality was still significant ($p < .05$). As the original data had no negative or null values, a log transformation was performed with no adjustment:

This resulted in a significant test of normality (*p* < .005). A square root transformation was performed on the original data with no adjustment, which resulted in a non-significant test of normality (p = .07, skewness = -.007, kurtosis = -.374). Based on the above exploration, it was decided that the WDW score variable be calculated using a square root transformation.

Dimensional change card sort task

Scoring for the dimensional change card sort (DCCS) task (Zelazo, 2006) was based on that detailed in the NIH Toolbox technical manual (Zelazo et al., 2012). The task consisted of three trials as follows; pre-switch trial, post-switch trial, and border sort (see Chapter Three for more task detail). The results on errors were as follows: Pre-switch, *m* = 0; Post-switch, *m* = .22, *sd* =.101; Border sort, *m* = 1.44, *sd* =.184. A time cost analysis was conducted to identify the switch cost between trials. A repeated measures analysis of variance (ANOVA) was performed on the raw time scores per trial. The assumption of sphericity was not met (*p* < .001). Using a Greenhouse-Geisser correction, the results showed there was a significant main effect of trial (*F* (1.125, 101.217) = 37.592, *p* <.001). With regard to pairwise comparisons, there was no significant difference between pre (*m* = 29.37, *sd* =.703) and post (*m* =28.03, *sd* =.717) sorts as expected (*p* = .280). However, there was a significant difference between the pre and border sorts (*p* <.001) and post and border sorts (*p* <.001). With regard to non-linear trends, both the linear effect and quadratic effects were significant (*p* <.001 and *p* <.001 respectively). Exploration was then conducted on trial 2 (post) to trial 3 (border) time-cost. In order to avoid penalizing cases where the base time was very slow, the trial 2 to trial 3 time-cost was calculated as a percentage increase. The test of normality was significant (*p* < .001, Skewness = .39 and kurtosis = 2.14). The issue of normality was addressed by trimming one low score outlier and one high score outlier. This resulted in a non-significant test of normality (*p* = .447, skewness = .26, kurtosis = -.266). Based on the above exploration, it was decided that the DCCS switch cost variable be computed using the trial 2 to trial 3 time-cost as a percentage increase, with the single highest and single lowest scores trimmed.

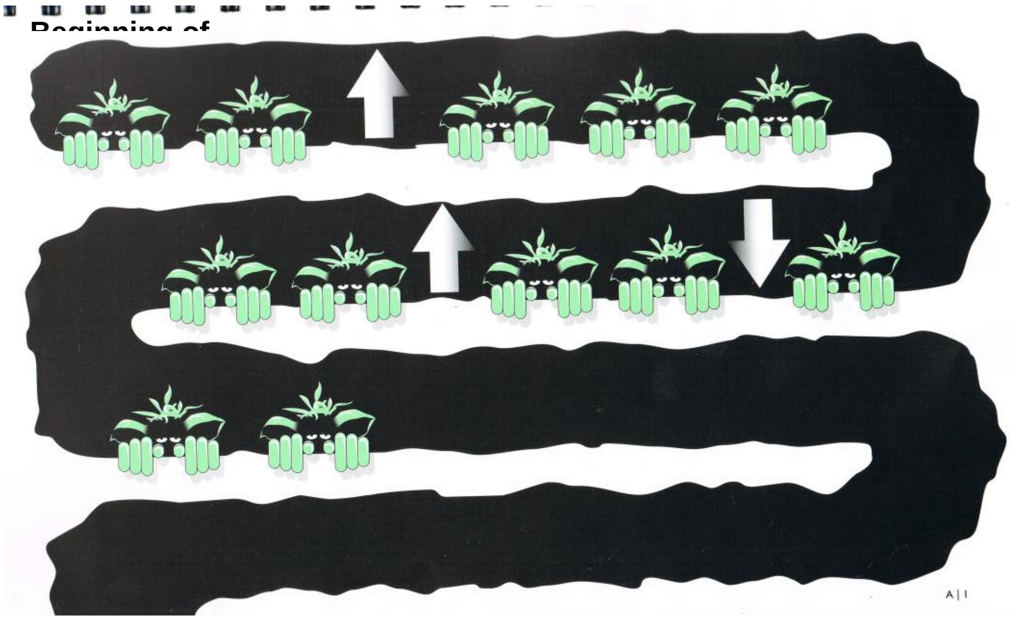
Colour Number Switch

Time-cost per trial was used as the scoring method for the colour-number switch (CNS) task. The task consisted of four trials as follows; an initial pre-switch trial (blue circles only), a post-switch trial (red circles only), an alternate blue trial (switching from blue to red) and an alternate red trial (switching from red to blue). Full task details are described in Chapter Three; Methodology. To determine that this scoring method was robust, a repeated measures ANOVA was performed on the raw time scores per trial. The assumption of sphericity was not met (p < .001). Using a Greenhouse-Geisser correction, the results showed there was a significant main effect of trial (F (3.005, 278.035) = 161.988, p < .001). With regard to non-linear trends, both the linear effect and quadratic effects were significant (p < .001 and p <.001, respectively). Pairwise comparisons were significant for trial 3 to trial 4 (p < .001). The remaining comparisons were not significant; trial 1 to trial 2 (p = .892), trial 1 to trial 3 (p = .069), and trial 2 to trial 3 (p = .911). Therefore, exploration was conducted on trial 3 to trial 4 time-cost to assess normality. This showed normal skew (-.089) with high and low score outliers. The test of normality was significant (p <.05, kurtosis = 2.524). The following steps were taken to normalize the data. Two outliers (i.e. one high, one low) were identified and trimmed. This improved kurtosis (-.436) and skewness (.074), and resulted in a non-significant test of normality (p = .339). To investigate whether the data could be normalized without losing cases, the data were converted to z-scores. The two same cases were identified as lying more than 2.5 standard deviations from the mean and were substituted with the preceding value. After which, the test of normality was not significant (p =.343, skewness = .061, kurtosis = -.281). Based on the above exploration, it was decided that the CNS time cost from trial 3 to trial 4 (i.e. as a percentage of their time from trial 3) be winsorized and used as the score for this task.

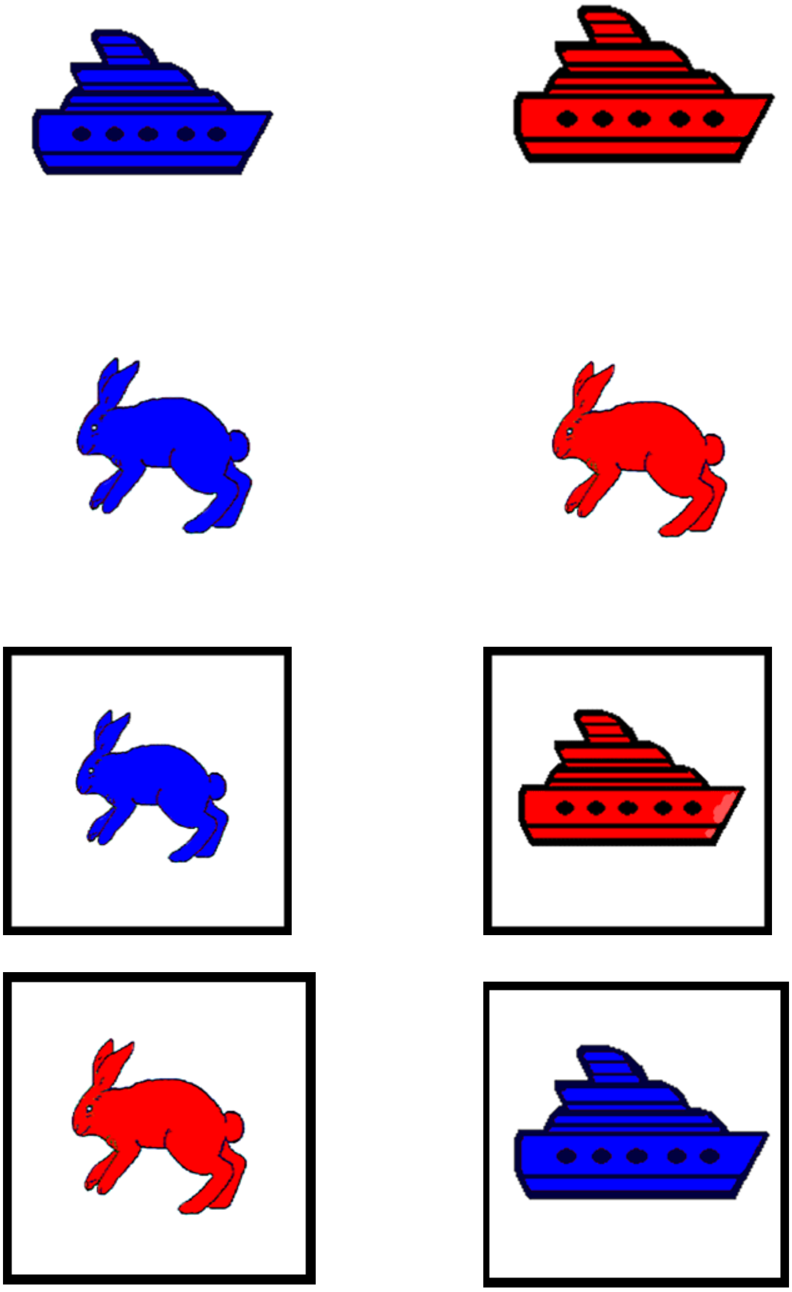
Creature Counting

Initial exploration was conducted on the standard score as calculated in the task administration manual from The Test of Everyday Attention for Children (TEA-Ch; Manly, et al., 2001). This score was calculated by dividing the total time for all correct trials by the total number of switches in those trials and then converting the score using the norm tables provided. Exploratory analysis on this data showed normal distribution indicated by a non-significant test of normality (p = .501, Skewness = -.003, kurtosis = -.173). As such, the Creature Counting standard score was used with no trimming, winsorizing or transformations.

Appendix E: Creature Counting Stimuli Example

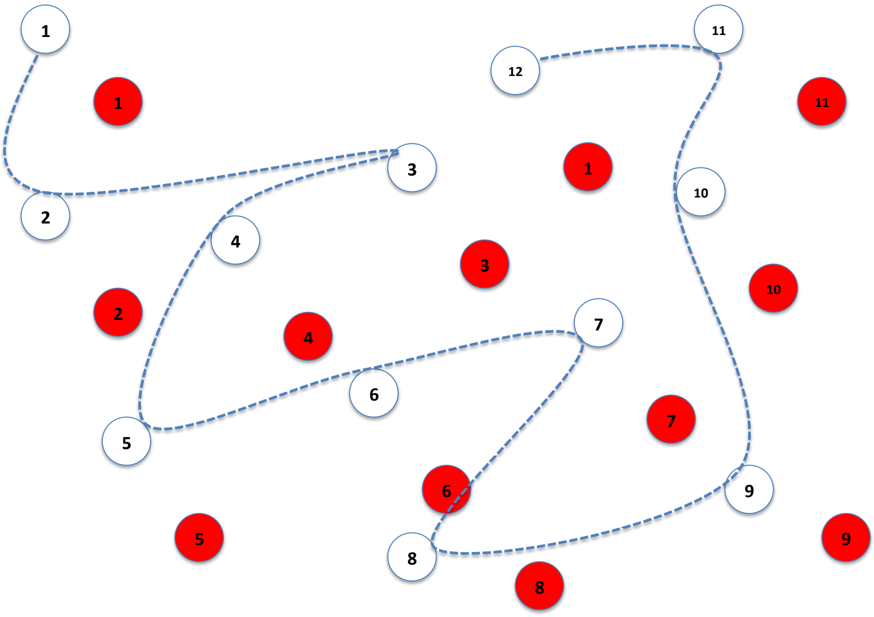


Appendix F: Dimensional Change Card Sort Task Stimuli

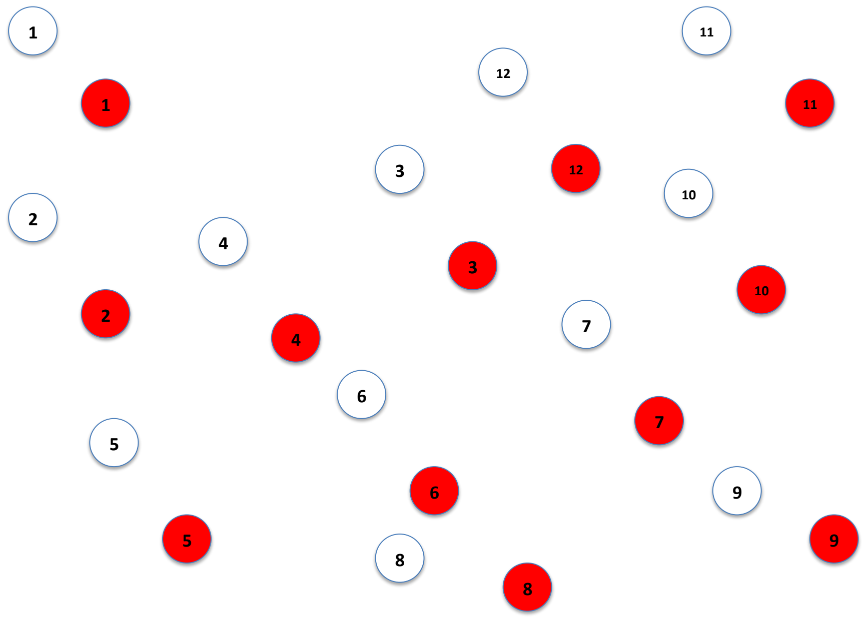


Appendix G: Colour Number Switch Stimuli

1) Base-line task stimuli



2) Pre and post switch task stimuli



Appendix H: Regressions for Chapter Four

Counting Span

Non-verbal reasoning

The experimenter-led task performance was entered as a predictor in Step 1 of the hierarchical regression analysis explaining 19.1% of the variance in non-verbal reasoning. When the computer-paced task performance was then entered as a predictor in Step 2, total variance explained by the model was 21.1%, F (2, 87) = 11.6, p < .001. Performance on the computer-paced counting span task did not explain a significant amount of additional variance (R^2 = change .02, F change (1, 87) p = .15).

This analysis was then conducted in reverse, entering computer-paced performance as a predictor at Step 1, explaining 12.2% of the variance in non-verbal reasoning. When performance on the experimenter-led counting span task was entered at Step 2, an additional 8.9% of the variance in non-verbal reasoning was explained, R^2 change = .09, F change (1, 87) p < .005).

In the final model, only performance on the experimenter-led task accounted for a significant amount of unique variance in non-verbal reasoning (β = .35, p < .005), after controlling for computer-paced performance. The amount of variance shared by both counting span tasks was 10%. This was calculated using a method employed by Bailey (2012). The amount of unique experimenter-led counting span variance, and the amount of computer-paced counting span variance were subtracted from the total variance (i.e. .21 - .02 - .089 = .10). Therefore, 48.1% of the variance explained in non-verbal reasoning performance is shared between the two versions of the counting span task.

Reading

The experimenter-led task performance was entered as a predictor in Step 1 of the hierarchical regression analysis explaining 7% ($p < .05$) of the variance in reading ability. When the computer-paced task performance was then entered as a predictor in Step 2, total variance explained by the model was 9.7%, F (2, 87) = 4.7, $p < .05$. Performance on the computer-paced counting span task did not explain a significant amount of additional variance after controlling for experimenter-led counting span task performance, R^2 = change .03, F change (1, 87) $p = .12$.

This analysis was then conducted in reverse, entering computer-paced performance as a predictor at Step 1, explaining 7.7% of the variance in reading ability. Performance on the experimenter-led counting span task did not explain a significant amount of additional variance after controlling for computer-paced counting span task performance (R^2 = change .02, F change (1, 87) $p = .17$).

In the final model, performance on neither the experimenter-led task ($\beta = .19$, $p = .12$), nor the computer-paced task ($\beta = .17$, $p = .17$) accounted for a significant amount of unique variance in reading ability. The amount of variance shared by both counting span tasks was 5.1%. This was calculated by subtracting the amount of unique experimenter-led counting span variance, and the amount of computer-paced counting span variance from the total variance (i.e. .097 - .026 - .02 = .051). Therefore, 52.5% of the variance explained in non-verbal reasoning performance is shared between the two versions of the counting span task.

Mathematics

The experimenter-led task performance was entered as a predictor in Step 1 of the hierarchical regression analysis explaining 37.5% of the variance in mathematics ability. When the computer-paced task performance was then entered as a predictor in Step 2, total variance explained by the model was 44.4%, F (2, 87) = 34.7, $p < .001$. Performance on the computer-paced counting span task explained an additional 6.8% of the variance in mathematics ability after controlling for experimenter-led counting span task performance (R^2 = change .068, *F* change (1, 87) $p < .005$).

This analysis was then conducted in reverse, entering computer-paced performance as a predictor at Step 1, explaining 29.7% of the variance in mathematics ability. When entered in Step 2, performance on the experimenter-led counting span task explained an additional 14.7% of additional variance after controlling for computer-paced counting span task performance (R^2 = change .15, *F* change (1, 87) $p < .001$).

In the final model, both the experimenter-led task ($\beta = .45$, $p < .001$), and the computer-paced task ($\beta = .31$, $p < .005$) accounted for a significant amount of unique variance in mathematics ability, with performance on the experimenter-led task being the better predictor. The amount of variance shared by both counting span tasks in mathematics ability was 22.9%. This was calculated by subtracting the amount of unique experimenter-led counting span variance, and the amount of computer-paced counting span variance from the total variance (i.e. .444 - .147 - .068 = .229). Therefore, 51.5% of the variance explained in non-verbal reasoning performance is shared between the two versions of the counting span task.

Listening Span

Non-verbal reasoning

When experimenter-led task performance was entered as a predictor in Step 1, it explained 3.7% of the variance in non-verbal reasoning. However, this was not significant (F (1, 89) = 3.4, $p = .068$). When performance on the computer-paced task was entered at Step 2, the total variance explained by the model was 7%, F (2, 88) = 3.3, $p < .05$. Performance on the computer-paced listening span task did not explain significant additional variance in non-verbal reasoning after controlling for experimenter-led counting span task performance (R^2 = change .034, *F* change (1, 88) $p = .09$).

This analysis was then conducted in reverse, entering computer-paced performance as a predictor at Step 1, explaining 6.9% of the variance in non-verbal reasoning. When entered in Step 2, performance on the experimenter-led listening span task explained an additional 2% of additional variance after controlling for computer-paced counting span task performance. However, this change was not significant (R^2 = change .002, *F* change (1, 88) $p = .070$).

In the final model, performance on neither the experimenter-led task ($\beta = .05$, $p <= .70$), nor the computer-paced task ($\beta = .23$, $p = .08$) accounted for a significant amount of unique variance in non-verbal reasoning. The amount of variance shared by both listening span tasks was 3.4%. This was calculated by subtracting the amount of unique experimenter-led span variance, and the amount of computer-paced span variance from the total variance (i.e. .07 - .034 - .002 = .034). Therefore, approximately 48.6% of the variance explained in non-verbal reasoning performance is shared between the two versions of the listening span task.

Reading

When experimenter-led task performance was entered as a predictor in Step 1, it explained 5.7% ($p < .05$) of the variance in reading ability. After performance on the computer-paced task was entered at Step 2, the total variance explained by the model was 9.4%, F (2, 88) = 4.58, $p < .05$. Performance on the computer-paced listening span task did not explain significant additional variance in reading ability ability after controlling for experimenter-led counting span task performance (R^2 = change .04, *F* change (1, 88) $p = .06$).

This analysis was then conducted in reverse, entering computer-paced performance as a predictor at Step 1, explaining 8.9% ($p < .005$) of the variance in reading ability. When entered in Step 2, performance on the experimenter-led listening span task explained an additional 5% of additional variance after controlling for computer-paced span task performance. However, this change was not significant (R^2 = change .002, F change (1, 88) p = .48).

In the final model, performance on neither the experimenter-led task (β = .09, p <= .48), nor the computer-paced task (β = .24, p = .06) accounted for a significant amount of unique variance in reading ability. The amount of variance shared by both listening span tasks was 5.2%. This was calculated by subtracting the amount of unique experimenter-led span variance, and the amount of computer-paced counting span variance from the total variance (i.e. .097 - .04 - .005 = .052). Therefore, approximately 53.6% of the variance explained in reading ability is shared between the two versions of the listening span task.

Mathematics

When experimenter-led task performance was entered as a predictor in Step 1, it explained 9.2% (p < .005) of the variance in mathematics ability. After entry of performance on the computer-paced task was entered at Step 2, the total variance explained by the model was 18.9%, F (2, 88) = 10.25, p < .001. Performance on the computer-paced span task explained an additional 9.7% of the variance in mathematics ability after controlling for experimenter-led span task performance (R^2 = change .097, F change (1, 88) p < .005).

This analysis was then conducted in reverse, entering computer-paced performance as a predictor at Step 1, explaining 18.7% (p < .001) of the variance in mathematics ability. When entered in Step 2, performance on the experimenter-led listening span task explained an additional 2% of additional variance after controlling for computer-paced span task performance. However, this change was not significant (R^2 = change 0.002, F change (1, 88) p = .61).

In the final model, only performance on the computer-paced task (β = .39, p < .005), accounted for a significant amount of unique variance in mathematics ability.

The amount of variance shared by both listening span tasks was 9%. This was calculated by subtracting the amount of unique experimenter-led counting span variance, and the amount of computer-paced counting span variance from the total variance (i.e. .189 - .097 - .002 = .09). Therefore, approximately 47.6% of the variance explained in mathematics ability is shared between the two versions of the listening span task.

Odd One Out Span

Non-verbal reasoning

When experimenter-led task performance was entered as a predictor in Step 1, it explained 3.7% of the variance in non-verbal reasoning, but was not significant (p = .26). The total variance explained in non-verbal reasoning by the model was not significant when performance on the computer-paced task was entered at Step 2, F (2, 59) = 1.1, p = .34. When the reverse analysis was conducted, the variance explained by the model remained non-significant (Step 2 R^2 change = 0.002, F change (1, 59) = .15 p = .70).

Reading

When experimenter-led task performance was entered as a predictor in Step 1, it explained 0.9% of the variance in reading ability, which was not significant (p = .47). The total variance explained in reading ability by the model was not significant when performance on the computer-paced task was entered at Step 2, F (2, 59) = 0.94, p = .40. When the reverse analysis was conducted, the variance explained in reading ability by the model remained non-significant (Step 2 R^2 change = <0.0001, F change (1, 59) = 0.009 p = .92).

Mathematics

When experimenter-led task performance was entered as a predictor in Step 1, it explained 5.9% (p = .06) of the variance in mathematics ability. After entry of performance on the computer-paced task was entered at Step 2, the total variance explained by the model was 21.5%, F (2, 59) = 8.09, p < .005. Performance on the computer-paced span task explained an additional 15.6% of the variance in mathematics ability after controlling for experimenter-led span task performance (R^2 = change .156, F change (1, 59) p < .005).

This analysis was then conducted in reverse, entering computer-paced performance as a predictor at Step 1, explaining 21.4% (p < .001) of the variance in mathematics ability. When entered in Step 2, performance on the experimenter-led listening span task explained an additional 0.1% of additional variance after controlling for computer-paced counting span task performance. However, this change was not significant (R^2 = change 0.002, F change (1, 59) p = .77).

In the final model, only performance on the computer-paced task (β = .49, p < .005), accounted for a significant amount of unique variance in mathematics ability. The amount of variance shared by both odd one out span tasks was 5.8%. This was calculated by subtracting the amount of unique experimenter-led span variance, and the amount of computer-paced span variance from the total variance (i.e. .215 - .156 - .001 = .058). Therefore, approximately 26.9% of the variance explained in mathematics ability is shared between the two versions of the odd one out span task.

Appendix I: Mean values for underlying mechanisms for the experimenter-paced and computer-paced versions of each CST

Table I.1: *Mean processing times, correlation and t test statistics for each CST across the three blocks.*

	Block 1 *(sd)*	Block *2* *(sd)*	Block 3 *(sd)*
Counting EL	2677.38 *(792.45)*	2880.85 *(853.78)*	2939.47 *(944.22)*
Counting CP	1790.90 *(599.70)*	1905.86 *(587.91)*	1886.00 *(603.87)*
r	.33**	.62***	.69***
(df) t	(89) 10.27***	(89) 13.74***	(89) 14.38***
Listening EL	4711.88 *(686.23)*	5421.41 *(767.85)*	5026.76 *(567.35)*
Listening CP	4206.16 *(472.90)*	4649.39 *(491.62)*	4564.96 *(446.98)*
r	.31**	.38***	.37**
(df) t	(85) 6.67***	(85) 9.70***	(64) 6.46***
Odd one out EL	2586.25 *(470.30)*	2933.40 *(679.87)*	2810.32 *(577.32)*
Odd one out CP	1916.16 *(383.18)*	2007.47 *(442.65)*	1980.67 *(341.74)*
r	.25	.26	.27
(df) t	(90) 12.14***	(90) 12.47***	(71) 12.00***

EL = experimenter-led, CP = computer-paced;

** p<.01; ***p<.001

Table I.2: *Mean recall times, correlation and t test statistics for each CST across the three blocks.*

	Block 1 *(sd)*	Block *2* *(sd)*	Block 3 *(sd)*
Counting EL	1381.04	1325.54	1209.06
	(423.25)	*(596.94)*	*(628.34)*
Counting CP	1240.51	987.27	983.54
	(410.43)	*(510.59)*	*(591.61)*
r	.26	.39***	.39***
t	(89) 2.63	(89) 5.21***	(89) 3.17**
Listening EL	2914.59	10292.28	19105.51
	(1772.39)	*(4079.87)*	*(7132.79)*
Listening CP	1833.22	7027.17	13424.85
	(930.79)	*(3516.19)*	*(4913.72)*
r	.13	.28	.40
t	(88) 5.39***	(88) 6.73***	(67) 6.83***
Odd one out EL	1547.73	3867.76	5586.77
	(451.57)	*(1269.40)*	*(1879.58)*
Odd one out CP	1110.25	2989.89	4452.44
	(362.42)	*(1074.64)*	*(1335.95)*
r	.27	.45***	.21
t	(90) 8.44***	(89) 6.72***	(70) 4.38***

EL = experimenter-led, CP = computer-paced;

** $p<.01$; *** $p<.001$

Table I.3: *Mean processing accuracy scores, correlation and t test statistics for each CST across the three blocks.*

	Block 1 *(sd)*	Block *2* *(sd)*	Block 3 *(sd)*
Counting EL	.99	.99	.99
	(.04)	*(.02)*	*(02)*
Counting CP	.90	.90	.87
	(.16)	*(.12)*	*(.11)*
r	-.08	.07	.73
t	(89) 5.03***	(89) 7.76***	(89) 10.82***
Listening EL	.98	.93	.98
	(.07)	*(.07)*	*(.04)*
Listening CP	.98	.91	.94
	(.06)	*(.07)*	*(.10)*
r	.29	.12	.53
t	(85).27	(85) 1.95	(64) 2.92
Odd one out EL	.99	.98	.99
	(.05)	*(.05)*	*(.03)*
Odd one out CP	.96	.92	.93
	(.09)	*(.10)*	*(.10)*
r	.03	-.01	.44
t	(90) 2.55	(90) 5.10***	(79) 4.97***

EL = experimenter-led, CP = computer-paced;

** p<.01; ***p<.001

Appendix J: The key components of the UK mathematics curriculum

Children in UK primary schools are taught mathematics based on the Primary Strategy (DfES, 2003), which consist of the following key learning components: Understanding number, calculation, problem solving, shape (including space and measure), and handling data. Summaries of learning outcomes are also provided.

Understanding number

Understanding number extends from basic counting principles in the early school years to negative numbers, place value, fractions, decimals and percentages in later primary school. Upon entering Year 5 children should have an understanding of counting in multiples, negative numbers, place value, order and comparisons above 1,000 and rounding numbers to the nearest decimal. Furthermore, children should be able to solve problems using all of these skills (DfES, 2003).

Calculation and problem solving

Calculation includes knowledge of operations (i.e. multiplication, division), commutativity (i.e. reversing an addition sum has no effect of the result but reversing the operands in a subtraction produces a different sum), and number facts (i.e. retrieving sums from long-term memory as opposed to calculation). Upon entering Year 5, children should be proficient in mental maths for three-digit numbers, using calculators for more complex operations and fact-checking results. Also, problem solving becomes more complex, with the introduction of multiple steps (DfES, 2003).

Shape, space and measure

Shape includes understand names of geometric shapes, and their properties (e.g. symmetry, acute, obtuse angles). Space refers to the ability to plot shapes on a grid and describe movement (e.g. to the left or right). Upon entering Year 5, children should be proficient in plotting shapes on a two-dimensional grid, provide co-ordinates for shape location dependent on given directions and complete complex shapes (e.g. complete an octagon when two sides are missing) (DfES, 2003).

Handling data

Handling data refers to the knowledge of basic statistics including the use of bar charts, line graphs. Children entering Year 5 are assumed to be able to solve problems using information presented in charts, tables and graphs. In addition, they should be proficient in collecting and providing information in the format of graphs and charts. It is assumed they will be able to interpret information presented in a graph for practical purposes such as demonstrating time related increases or decreases (DfES, 2003).