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Development of Speed, Memory, and Fluid Reasoning in Children

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DEVELOPMENT OF SPEED, MEMORY,

AND FLUID REASONING IN CHILDREN

by

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ABSTRACT OF THE DISSERTATION

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Children's memory and higher-order cognitive abilities such as fluid reasoning improve with age, but the relationships between these abilities are not well understood. The developmental cascade model proposed by Fry and Hale (1996) suggests that age related improvements in speed of processing are related to improvements in working memory, which in turn influence fluid reasoning. Recent research in adults suggests secondary memory is also an important predictor of fluid reasoning. The relations between working memory and fluid reasoning have been studied extensively in both adults and children. However, the relationships between working memory, secondary memory, and fluid reasoning have not been simultaneously examined in children.

In this study 113 children (6 to 12 years of age) completed a battery of cognitive tests including speed of processing, working memory, secondary memory, and fluid reasoning. Correlation, regression, and path analyses were used to better understand the relationships between working memory, secondary memory, and fluid reasoning. Results indicated that only working memory accounted for significant unique variance in predicting fluid reasoning in children. Secondary memory influenced fluid reasoning indirectly by mediating the relations between speed and working memory.

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OVERVIEW

Children’s ability to process information faster matures with age (e.g., Hale, 1990). Similarly, children’s short-term memory capacity (Dempster, 1981) and reasoning abilities (Carlson & Jensen, 1982) show age-related improvement. The developmental cascade model proposed by Fry and Hale (1996) explored the relations among these three variables. The cascade model showed that age-related improvement in speed of processing was directly related to age-related improvement in working memory, which in turn influenced improvement in fluid reasoning. Thus, the effect of age-related improvement in processing speed on fluid reasoning was mediated by working memory.

Evidence for the developmental cascade model has been found in both children and adults (Demetriou, 2002; Kail, 2007; Nettelbeck & Burns, 2010; & Salthouse, 1991). Although some studies show that a large proportion of the variance in fluid reasoning can be accounted for by speed-related improvements in working memory (e.g. de Riabaupierre & Lecerf, 2006; Nettelbeck & Burns, 2010), others show that there is a significant proportion of age-related variance in fluid reasoning that is not explained by changes in speed and working memory (Fry & Hale, 2000).

Recent work by Unsworth and Engle (2006, 2007) suggests secondary memory as a possible candidate for the missing mediator in the developmental cascade model. The terms primary and secondary memory were first introduced by William James (1890). According to James, primary memory refers to the current contents of consciousness, whereas secondary memory refers to memories that need to be brought back to consciousness through retrieval. Even though literature often uses the terms short-term and long -term memory to refer to primary and secondary memory, more recent work by

Nash Unsworth and colleagues re-introduced James' original terms when discussing the relationship between working memory and long-term memory. For this reason, in the current study, I use the terms primary and secondary memory to refer to short-term and long-term memory. According to Unsworth and colleagues, primary memory refers to information that is currently fully activated (i.e., in the focus of attention according to Cowan's (1999) embedded processes model) whereas secondary memory refers to items that are outside the focus of attention. Cowan's model is described in greater detail in the literature review below.

Unsworth and Engle (2007) closely examined the relationship between working memory and fluid reasoning in healthy young adults. They suggested that one important function of working memory is the ability to retrieve information that has been recently displaced from the focus of attention (i.e., retrieval of information from secondary memory). Moreover, these authors suggest that this function may be the key to understanding why measures of working memory do such a good job of predicting fluid reasoning in adults.

In a recent study, I explored the relationship between fluid reasoning and immediate and delayed recall in children ages 6 to 16 years. The results showed that children's reasoning was significantly correlated with retrieval from secondary memory (De Alwis, Myerson, Hershey, & Hale, 2009). Although this study demonstrates that secondary memory, like working memory, predicts fluid reasoning in children, I was not able to directly compare the two predictors. Despite the fact that the working memory system has been studied extensively in children, the potential role of secondary memory in children's fluid reasoning has not been fully explored.

The goal of the present study is to consider secondary memory as a possible mediator of age-related improvements in fluid reasoning in children and systematically explore the role of secondary memory within the context of the developmental cascade model. In addition, the current study should shed light on the relationship between the development of working memory and secondary memory to better understand why working memory is such a good predictor of fluid reasoning in children (Fry and Hale, 1996; Nettelbeck & Burns, 2010; de Riabaupierre & Lecerf, 2006).

In the next section I will present relevant literature concerning the relationships among age, processing speed, working memory, secondary memory, and fluid reasoning in children. As each section is introduced, each of these constructs will be defined and the terms used throughout this document will be further delineated.

LITERATURE REVIEW

Development of Speed of Processing

The construct of cognitive processing speed (referred to throughout as speed of processing) is one that has been studied for a very long time. Children's ability to process information more quickly improves with age (Cerella & Hale, 1994), and speed of processing appears to play an important role in memory development. For example, studies with both adults and children have shown that the greatest attenuation of age-related variance in working memory occurs after controlling for processing speed (e.g., Fry & Hale, 1996; Salthouse, 1996).

Researchers interested in understanding why speed of processing improves during childhood have suggested that the improvement may be directly related to brain maturation. The maturation of myelin, which insulate neurons, increases the speed at which neural impulses are transmitted. Many researchers have suggested that myelination may be the neurobiological mechanism underlying improvements in speed of processing in children (e.g., Hale, 1990; Rabinowicz, 1980). Although beyond the scope of the current study, it is now possible to obtain measures of white matter using neuroimaging to examine the relationship between myelination and processing speed. In the current study, however, I focus on behavioral measures of processing speed.

In studying the development of speed of processing, Hale (1990) proposed that there is a global developmental trend in speed of processing. Hale's hypothesis suggests that the age-related increase in speed is not specific to one task but is global in nature and that the time a child requires to complete a task can be identified as a proportion of the time required by an adult. To test this hypothesis, Hale collected data from children, adolescents, and young adults from the following four age groups: 10, 12, 15 and 19 years. Participants performed a battery of speeded reaction time tasks that included choice reaction time, letter matching, mental rotation and abstract matching. The results showed that for each of the three younger groups, performance on all four tasks was a precise linear function of the young adults' performance in the corresponding conditions.

Kail (1991a) provided supporting evidence for a speed of processing global developmental trend based on a meta-analysis of 72 studies. Consistent with Hale (1990), Kail found that processing speed in children increased linearly as a function of the processing speed of adults. In addition, Kail found that this increase was an exponential (non-linear) function. That is, initially speed of processing improves rapidly, but improvement becomes more gradual during late childhood and adolescence. Later research by Kail and colleagues (Kail, 1993; Kail & Park, 1992) further established that a non-linear function describes the developmental trajectory of speed of processing during childhood and adolescence. As an illustration, I took raw scores from the WISC-IV Cancellation subtest and calculated response time per item for different age groups. As seen in Figure 1, the response times show a non-linear decrease as a function of age.

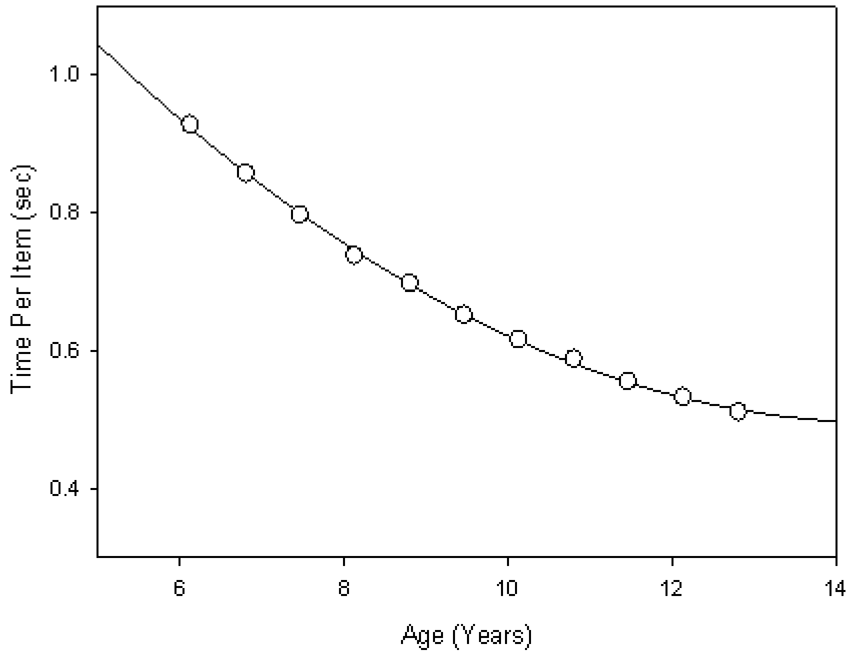


Figure 1. Response time per item calculated using raw scores from the Cancellation subtest of the WISC-IV. Response time per item is plotted as a function of age. Data were taken from the WISC-IV Administration and Scoring Manual (2003), Table A1 (Appendix A).

Kail and Miller (2006) further explored the global developmental trend comparing response latencies in verbal and nonverbal tasks. Children between 9 and 14 years of age were tested on 10 different speed tasks. The results supported the global developmental trend in which children's response times increased linearly as a function of adult's response times in the same conditions. In comparing the verbal and nonverbal domains, it was found that response times on tasks from both domains showed a linear increase as a function of age. At age 9 years, there was a difference in the rate of development between the two domains (the slope was steeper for nonverbal than verbal tasks), but this difference was not apparent by age 14 years. However, one problem in trying to determine whether there are domain-specific differences in verbal and nonverbal processing speed (a difference that is observed in late adulthood) is that children are still acquiring vocabulary and expanding their knowledge base. As such, differences in knowledge base may interact with actual differences in speed of processing across verbal and nonverbal domains.

In summary, in the area of cognitive development, speed of processing is an important topic because the ability to process information faster appears to facilitate the development of many cognitive abilities. Moreover, almost all research conducted since the body of work reviewed by Fry and Hale (2000) has continued to confirm that the developmental improvements in task-independent processing speed are orderly and follow an exponential, negatively-accelerated trajectory of improvement between the ages of 6 and 16 years.

Development of Working Memory

The construct of working memory is discussed in many areas of psychology, including cognitive psychology, clinical neuropsychology, and cognitive neuroscience. However, both across and within these disciplines, researchers have varied opinions of the definition of working memory. The general consensus is to define working memory in relation to both storage and processing of information. However, in the literature the term "working memory" is at times used to refer only to storage, only processing, or a combination of the two. For the purpose of this study, I use the term working memory in reference to both storage and processing of information.

In this section I will briefly discuss the history of working memory in relation to short-term memory and provide an overview to the working memory model proposed by Baddeley and Hitch (1974). Other models of working memory proposed by Cowan, Oberaurer, and Unsworth and Engle will be addressed in a subsequent section in which I discuss the relationship between working memory and secondary memory.

Baddeley's Model of Working Memory

In the 1960s, the term short-term memory was used to describe the retention of small amounts of information over brief time intervals (Baddeley, 2000a). However, in the 1970's, the original concept of short-term memory was incorporated with the more complex framework of a working memory system. Within the multi-component system of working memory, short-term memory became a subcomponent responsible for the storage function (Baddeley & Hitch, 1974). Baddeley and Hitch (1974) used the term working memory to refer to a system comprising multiple components. They emphasized the functional importance of the system as opposed to simple storage and indicated that the system was involved in both the temporary maintenance and manipulation of information (Baddeley, 2001). The original model of working memory consisted of three components, the phonological loop, the visual-spatial sketch pad (both referred to as slave systems), and the central executive which coordinated the functions of the two subsystems. The following subsections provide a brief description of each of these subcomponents.

Phonological loop. The phonological loop is assumed to consist of two subcomponents, a phonological store and an articulatory rehearsal system. The phonological loop is generally associated with the storage of verbal information. For example, when a series of digits is presented, memory traces of the digits within the store decay over a period of a few seconds unless they are refreshed through rehearsal. According to Baddeley (2006), apart from refreshing and maintaining verbal information, the phonological loop has a second function which is to convert visually-presented material into a phonological code. As a result, there is little difference in memory for digits that are presented visually or auditorily, because visual digits can be converted into a phonological code and then covertly rehearsed .This process of subvocal rehearsal can be prevented by a technique called articulatory suppression, in which one is asked to vocalize a task irrelevant term such as “the” during the presentation of visual material (Baddeley, 2006).

A clear indicator of the use of the phonological store is a phenomenon termed the *phonological similarity effect*. This phenomenon suggests that items that are similar in sound (D, G, P, T, V) are recalled more poorly than items that are dissimilar (F, K, R, W, Y) (Conrad & Hull, 1964). Baddeley (1966a) found a similar effect in which recall of rhyming words such as cat, mat, hat, man, can was poorer compared with non-rhyming words such as pit, day cow, pen. Baddeley (1966b) showed that this phenomenon was only related to the short-term memory store by increasing the number of items presented and providing several learning trials. Long list lengths and repeated learning eliminated the phonological similarity effect because the meaning of the words became more important than the sound.

Another phenomenon, the *word length effect*, was considered by Baddeley, Thomson, and Buchanan (1975) to be an indicator of the articulatory rehearsal process. As the name implies, recall of single syllable words such as cow, pen, tree, and book is better than recall of polysyllabic words such as refrigerator, university, electricity, and opportunity (Baddeley, 2006). Polysyllabic words are recalled less accurately because longer words take longer to articulate during rehearsal, thereby lengthening the amount of time during which decay or interference can occur (Baddeley, 2006).

Visual-Spatial Sketchpad. This component of the working memory system is involved in temporarily maintaining visual and spatial information. Unlike the phonological loop, which has been studied extensively, the sketchpad has not been widely explored. Although research has focused on establishing the potential separability of the visual and spatial subcomponents, finding tasks that are pure measures of each component has been a challenge, mostly because visual information can be verbally encoded (Baddeley, 2001). The visual-spatial sketchpad can be interrupted by motor movements such as tapping or touching specific locations (Baddeley & Liberman, 1980), by eye movements (Lawrence, Myerson, Oonk, & Abrams, 2001), or by presenting irrelevant visual patterns or noise (Logie, 1986) .

The Central Executive. The central executive is generally known to be the least understood component of working memory (Baddeley, 2006). Even though the term "executive function" is extensively discussed in the literature, there is little consensus regarding the distinctive functions that fall under the umbrella of "executive." Executive functions include functions such as inhibiting task- irrelevant information, updating the memory system with relevant information, switching attention between tasks, and dividing attention among tasks. (Baddeley, 2001).

The Episodic Buffer. A fourth component was introduced by Baddeley (2000b) to the working memory model to address some phenomena that did not fit the pattern of data reflecting the functions of the tripartite working memory system. For example, when a series of numbers are visually presented along with an articulatory suppression task (during which the participant repeats the word "the"), participants still recall a fair number of digits (the span might drop from seven to five items) (Baddeley, 2000b). This finding raises the question as to how the digits were stored because the phonological loop was occupied with the suppression task.

Also, in a typical word span task, many participants begin to make errors after five or six words. If these words form a meaningful sentence, however, it is possible for participants to recall a number of words that exceeds their memory span (Baddeley, 2000b). This also raises the question of how these words were stored. These findings led Baddeley and colleagues to re-evaluate the original three component working memory model and introduce the fourth component named the episodic buffer. According to Baddeley (2000b), the two main functions of the episodic buffer include integrating information from the verbal and spatial system and linking long-term memory and working memory. The link between long-term memory and working memory presages the work by Unsworth and Engle who suggest that all complex working memory tasks reflect a reliance on not just primary memory (i.e., short-term storage, or items currently fully activated in the focus of attention) but also secondary memory (i.e., items that are outside the focus of attention).

The Baddeley and Hitch (1974) model of working memory has been examined in a number of studies with children (Gathercole et al. 2004; Alloway, Gathercole and Pickering, 2006). Gathercole et al. (2004) tested a large group of children between the ages of 4 and 15 years on a battery of working memory tasks. The battery consisted of simple and complex verbal and spatial working memory tasks. The simple tasks were used as storage measures that predicted the function of the phonological loop and the visual-spatial sketchpad. The complex tasks were used as measures of the central executive. The purpose of the study was to determine whether the structural organization of working memory changed across childhood.

In this study data were analyzed only from age 6 upwards because some of the tasks were not administered to the youngest age groups. Confirmatory factor analysis revealed there were three separate factors. The best fitting model showed that complex working memory tasks loaded on factor1, the simple storage verbal tasks loaded on factor 2, and the simple storage spatial tasks loaded on factor 3. This was in keeping with the three main components of Baddeley and Hitch's (1974) initial model of working memory consisting of the central executive, phonological loop and visual-spatial sketchpad. The results further showed that the central executive component was linked to both the phonological loop and the visual-spatial sketchpad, but the two latter components were independent of each other (Gathercole et al, 2004).

Alloway, Gathercole and Pickering (2006) supported these results by testing a larger group of children between ages 4 and 11 years on similar tasks. In this study confirmatory factor analysis again revealed three separate factors that supported the Baddeley and Hitch (1974) model, indicating that the structural organization of working memory is established even at the early age of four years. However, the results indicated a functional change in this organization across childhood. The youngest group of children (4-6 years) showed a very strong relationship between visual-spatial and the central executive components but this relationship decreased with age.

It has been established by a number of researchers that working memory span increases with age, showing a steady increase from preschool years through adolescence (e.g., Case, Kurland & Goldberg, 1982; Dempster, 1985). There are several underlying mechanisms that have been proposed to explain this age-related increase in memory span. Increase in speed of processing helps to improve working memory span (Cowan, 1997; Kail, 1991b; Fry & Hale, 1996). Speed plays an obvious role in terms of maintaining information in the verbal working memory slave system through subvocal rehearsal, but the role of speed within the visual-spatial slave system is not known. However, it is important to note that faster processing can facilitate different strategies (e.g., chunking, imagery) that may be used to better maintain verbal or spatial information before recall.

In the case of the phonological loop, memory capacity increases as a result of efficiency in rehearsing information. As children grow older they are able to maintain a larger amount of verbal material due to their ability to rehearse the information more quickly (Hulme et al., 1984). However, this ability to spontaneously rehearse information is very limited before the age of 7 years (Gathercole & Hitch, 1993).

During early childhood, children use the visual-spatial sketchpad to remember visual information. However, this changes by about age 7. At this time children are able to recode visual material into phonological forms and tend to use the phonological loop to mediate performance on spatial tasks (Hitch & Halliday, 1983; Hitch, Halliday, Schaafstal & Schraagen, 1988).

This question was explored in a study by Hitch and Halliday (1983) in which children 6, 8 and 10 years were asked to recall sequences of spoken words or a corresponding set of pictures. The words varied in length with one, two or three syllables. The results indicated that the two older groups showed the word length effect (recalling more shorter words than longer words) for both the auditory and pictorial conditions, whereas the youngest group showed this effect only for the spoken words. These results support the fact that, unlike older children who spontaneously recode visual material into words, younger children do not do so.

However, the interesting question of how memory span for abstract patterns that cannot be verbally recoded still increases with age is not fully understood (e.g. Pickering, Gathercole, Hall & Lloyd, 2001). Researchers have suggested that this could be a result of changes in the working memory structure, such as increases in storage capacity of the visual-spatial sketchpad (Logie & Pearson, 1997) or other age-related changes including the effective use of strategies, accumulation of knowledge relating to visual-spatial structures, and improvements in executive functions (Gathercole et al. 2004).

A study by Hale, Bronik and Fry (1997) explored the development of executive functions by studying children's ability to resist interference and remember task-relevant information. In this study, children 8, 10 and 19 years of age were tested on a series of complex working memory tasks. The working memory tasks included conditions in which interference was caused by an interleaved secondary task from either the same or different domain (verbal versus spatial). In the verbal task, children were shown a series of numbers in which each number was of a different color; the interfering task was either to say the color aloud (verbal interference) or to touch the same color in a color palette (spatial interference). In the spatial task, participants had to remember different locations; the interfering task was either to say the color of the X that marked the location (verbal interference) or to touch the same color in a color palette (spatial interference).

The results of this study showed that only the 8 year olds showed evidence of cross-domain interference. That is, the secondary tasks from the same and different domain (verbal and spatial) both interfered with the working memory task (although the interference was greater for same domain relative to cross domain). In contrast, for the 10 year olds and adults, interference with working memory occurred only when the secondary task was from the same domain. These results suggest that the executive functions that are engaged when performing a complex span task (e.g., switching between tasks) reaches maturity somewhere between the ages of 8 and 10 years.

Development of Fluid Reasoning

The terms fluid reasoning and fluid intelligence are used interchangeably in the literature (Horn & Cattell, 1967; Horn & Hofer, 1992). In this study, I use the term fluid reasoning. I will begin with a general overview of intelligence (the larger construct that encompasses both fluid and crystallized abilities), followed by a discussion of the development of fluid reasoning.

The term fluid reasoning is often associated with the concept of intelligence or Spearman's "g". According to Spearman (1927), all abilities are correlated. For example, when examining children's test scores on a wide range of subjects, one could see that these scores are correlated although they measure a wide range of abilities. Spearman (1927) explains this phenomenon by stating that general intelligence or "little g" is the general factor that shares most of the variance between varied cognitive tasks.

In the 1960's Spearman's student Cattell disregarded the notion that intelligence is a single general factor. Cattell and Horn proposed two factors of general intelligence: fluid and crystallized or *gf* and *gc* (Horn & Cattell, 1967). Crystallized intelligence is learned knowledge and skills and is thought to be influenced by age, education, culture and experience. Fluid intelligence, on the other hand, is commonly known as the ability to reason and solve novel problems. It is an innate ability that is not determined by any of the external factors that influence crystallized intelligence (Cattell, 1971).

Over the years, different theories of intelligence have been proposed. After the distinction between fluid and crystallized intelligence, Horn (1985) and Horn and Hofer (1992) suggested that this dual concept of intelligence was not sufficient to explain the general abilities that contribute to intelligence. Accordingly, they proposed a multiple general factor concept of intelligence. According to this theory, intelligence consists of fluid and crystallized components in which the fluid component captures our ability to efficiently and accurately solve novel problems, whereas crystallized abilities capture our acquired knowledge (i.e., our database of semantic knowledge); in addition, it consists of other components that include visual-spatial reasoning, processing speed, and long and short-term memory and other components.

According to Horn and Hofer (1992), a significant distinction between fluid and crystallized intelligence can be seen when examining the growth curves of these abilities. Both g_f and g_c show improvements in early to mid childhood, but during older adulthood g_c shows an increase while there is a noticeable decline in g_f. Considering the development of fluid reasoning during childhood and adolescence, the growth pattern shows a non-linear function in which there is a greater increase in performance in early childhood and a more gradual increase during adolescence. Figure 2, which is presented below, provides clear evidence of this pattern observed in the normative sample data from the WISC-IV Matrix Reasoning subtest. The WISC-IV Matrix Reasoning subtest is known to be a reliable measure of fluid reasoning. Notably, the function describing performance on this subtest follows a negatively-accelerated growth function across three different levels of performance (the 25th, 50th and 75th percentiles).

Horn and Hofer (1992) further suggested that the pattern of decline in g_f to be similar to that of other abilities such as working memory and processing speed. They referred to these abilities as “vulnerable abilities” because they decline in older adulthood and also show irreversible impairment following brain damage (Horn & Hofer, 1992). Crystallized intelligence was known as a “maintained ability” that showed little or no decline with aging except in very late adulthood (Horn & Hofer, 1992). Considering

Horn and Hofer's (1992) hypothesis that vulnerable abilities show similar patterns of decline, several theories have been proposed linking speed of processing, working memory and fluid reasoning.

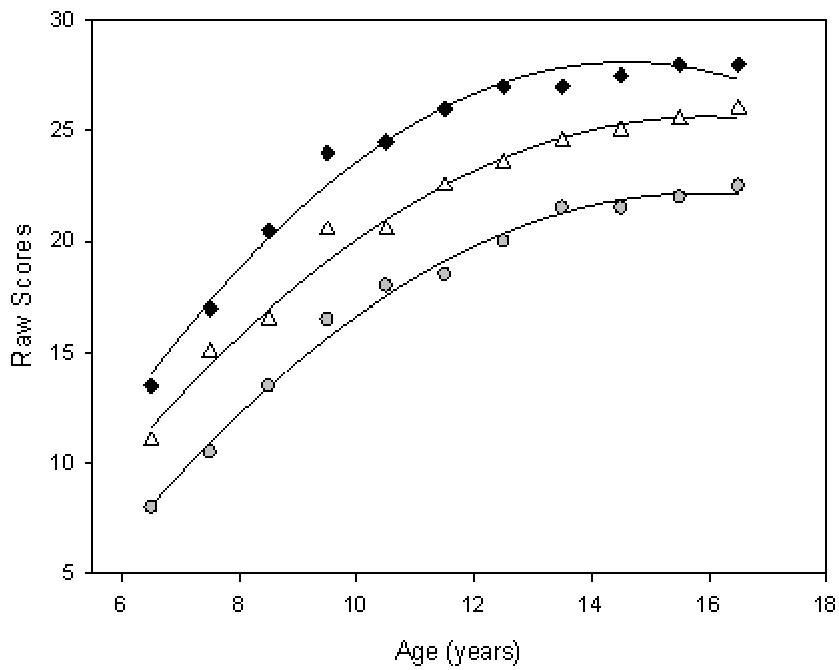


Figure 2. Raw scores from normative data from the WISC-IV Matrix Reasoning subtest plotted as a function of age. Data taken from the WISC IV Administration and Scoring Manual (2003), Table A1 (Appendix A). Three percentiles are shown: 25^{th}, 50^{th} and 75^{th} are represented by the circles, triangles and squares, respectively. The solid lines represent the best-fitting polynomial functions for each of the three percentiles.

Development of Age, Speed and Working Memory

The idea that age-related improvements in speed and working memory are related has been of interest to both developmental and aging researchers for many years. Existing literature provides substantial evidence to support this fact (e.g., Cowan et al. 1994; Hulme, Thomson, Muir, & Lawrence, 1984; Kail,1992; Kail & Park, 1994).

Processing information faster helps to prevent the loss of information while performing complex memory tasks. Losing information can take place either through decay of relevant information or by interfering information displacing the "to-be-remembered" information (Cowan, 1997). Faster processing minimizes the amount of information that is lost through interference and decay.

Hulme et al. (1984) showed that age-related increases in memory span can be predicted by speech rate. Kail (1992) supported this finding by showing that age and processing speed independently influenced articulation rate, which in turn was a good predictor of memory span.

In the Hulme et al. (1984) study, the researchers tested children of ages 4, 7 and 10 years and a group of younger adults. Memory span and articulation rate were measured using one, two and three syllable words. Articulation rate (words per minute) and span were determined for each word length. Overall, it was found that memory span was affected by the number of syllables. Memory span for words with multiple syllables was lower because the words took longer to say indicating that developmental increases in memory span could be attributed to articulation rate. Importantly, the relation between overt articulation rate and memory span was revealed to be a single, age-invariant function.

Kail (1992) supported these findings with data collected from 9 year old children and young adults. Participants completed speed of processing tests and measures of memory span. Their rate of articulation was also measured. Path analysis revealed that age-related differences in memory span were mediated by age-related differences in speed. When articulation rate was added to the model, it showed that a large amount of age-related improvement in articulation rate was mediated by speed. This finding was replicated by Kail and Park (1994) using children from United States and Korea.

More recently, Magimairaj et al. (2009) conducted a study with children between 6 and 12 years of age to find out the contributions of short-term memory storage, processing speed, and attentional allocation on working memory. Correlational analysis revealed that all three variables (storage, speed and attentional allocation) were significantly related to working memory performance after controlling for age. Furthermore, regression analysis showed that when age was controlled, both short-term storage and speed accounted for unique variance in working memory performance while attentional control did not. Overall, these researchers suggest that short-term storage and processing speed are important predictors of performance of working memory.

Development of Age, Speed, Working Memory and Fluid Reasoning

In this section I will focus my discussion on the developmental cascade model (Fry and Hale, 1996) along with supporting evidence. When describing the developmental cascade model, it is best to begin the discussion with reference to the *Speed Mediation Theory of Intelligence* proposed by Kail and Salthouse (1994). Kail and Salthouse (1994) believe neurobiological causes to be the underlying factors that bring about differences in intellectual functioning. The unique aspect of this theory is that it is not based on individual differences; instead, it is a developmental theory of age-related changes in speed, working memory and intelligence across the lifespan (Kail & Salthouse, 1994). Their work supports this hypothesis by providing evidence for improvement and decline in speed of processing, working memory and intelligence (in particular fluid reasoning) across the lifespan (Kail, 1991; Kail and Park 1994, Salthouse, 1991). Salthouse (1991) provided evidence that age-related changes in speed of processing accounted for all of the age-related changes in fluid reasoning during late adulthood, with the relationship between speed and fluid reasoning being mediated by working memory. Overall, the *Speed Mediation Theory of Intelligence* supports the idea that general speed of processing is an indirect determinant of age-related changes in fluid reasoning, whereas working memory is an important mediator in this relationship as it is the single best predictor of fluid reasoning and is itself directly affected by speed of processing.

Developmental Cascade Model

In keeping with the Speed Mediation model proposed by Kail and Salthouse (1994), Fry and Hale (1996) explored the relationship between speed of processing, working memory and fluid reasoning in children. The purpose of the study was to gain an understanding of the effects that age-related differences in processing speed and working memory had on age-related differences in fluid reasoning. The researchers tested 214 children, adolescents and young adults between the ages of 7 to 19 years. The speed tasks included disjunctive reaction time tasks, (two vertical arrows pointing in the same different directions requiring same/different judgment), shape classification (requiring same different shape judgment), visual search (requiring a target present absent judgment), and abstract matching (required participants to find the best match to a target pattern). Working memory was assessed using four different tasks assessing verbal and spatial working memory. In the simple verbal and spatial tasks, participants saw a series of digits and recalled these in the same order in which they were presented (verbal) or recalled specific locations on a grid that were cued by an X (spatial). In the complex working memory task participants reported the colors of the digits and Xs while maintaining the digit and location information in working memory. Fluid reasoning was measured using the standard Raven's Progressive Matrices test.

Using path analyses the researchers explored the relations between age, speed, working memory and fluid reasoning. Overall, the results showed that age-related increases in speed of processing influenced the development of working memory, which in turn influenced performance on the fluid reasoning task. Thus, it was found that both age-related and individual differences in working memory mediated the relationship between speed of processing and fluid reasoning. The paths in the developmental cascade model are shown in Figure 3.

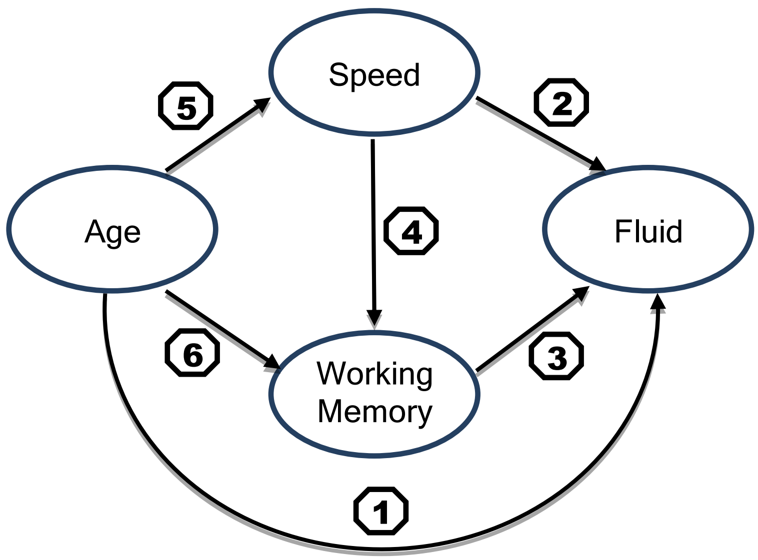


Figure 3. Schematic of the developmental cascade model depicting the paths between age, speed, working memory and fluid reasoning adapted from Fry and Hale (2000).

As shown in this path diagram, path 1 depicts the relations between age and fluid reasoning that is not explained by speed or working memory. According to Fry and Hale (1996), this path showed a path coefficient of .36. Path 2, the path between speed and fluid reasoning was not significant and showed a path coefficient of -.02, indicating that speed did not have a direct effect on fluid reasoning. Path 3 between working memory and fluid reasoning showed a coefficient of .38 whereas path 4 between speed and working memory showed a coefficient of -.51. Paths 5 and 6 between age and speed and age and working memory showed coefficients of -.86 and .22 respectively. Overall the results in Fry and Hale (1996) indicated that the relations between speed and fluid reasoning were mediated by working memory. Also, there was a significant proportion of age- related variance in fluid reasoning that was not explained by speed and working memory.

The results from Fry and Hale (1996) replicated and extended those of Kail (1991b) and Kail and Park (1994); they were also in keeping with the Kail and Salthouse (1994) model that was hypothesized but not tested in children. Kail (2007) provided further support for the developmental cascade model by providing longitudinal evidence. Children between 8 and 13 years were tested on a series of speed, working memory and Raven's Progressive Matrices in two testing sessions that were one year apart. These results further supported the developmental cascade model by providing stronger evidence for a causal relationship in which working memory has a direct influence on fluid reasoning, whereas the effect of speed was indirect.

Other recent studies have further explored the developmental cascade model and the findings have provided additional support for the developmental cascade. Demetriou, Constantinos, Spanoudis, & Platsidous (2002) conducted a 2 year longitudinal study of 8 to 14 year olds. Participants were tested on a large battery of speed of processing, working memory and problem solving tasks. Structural equation modeling showed that these variables were interrelated in a cascade fashion with speed influencing working memory performance, which in turn had a direct effect on problem solving.

de Riabaupierre & Lecerf (2006) conducted a cross-sectional study with children, young adults and older adults to assess the role of speed and working memory on fluid reasoning. The speed tasks included a letter comparison and pattern comparison test, the working memory measures included reading span and a matrices test, and the measure of fluid reasoning was the Raven Standard Progressive Matrices. In all three groups, the results supported the cascade model and results revealed that most of the age-related variance in fluid reasoning was accounted for by a combination of working memory and speed. The researchers also found a difference in the cascades between children, younger and older adults. They found speed to account for more age-related variance in the child and young adult groups while working memory accounted for more variance in the older adult group.

Nettlebeck and Burns (2010) conducted a study to explore the role of speed working memory and reasoning ability across the lifespan. The study tested children between the ages of 8 to 14 years and adults between the ages of 18 to 87 years. Multiple measures were used to measure speed and working memory while fluid reasoning was measured using the Cattell Culture Fair Test (which, unfortunately is a timed test and thus their measure of fluid reasoning is confounded by speed). The data provided supporting evidence of a cascade for both children and adults, where age-related changes in speed and working memory accounted for variance in age-related changes in fluid reasoning (although it would be ideal to replicate this finding using an untimed test to measure fluid reasoning). Similar to the de Riabaupierre & Lecerf (2006), Nettelbeck and Burns found that adults' age-related changes in working memory (which were not mediated by speed) made an independent contribution in explaining variance fluid reasoning. The child assessment of the cascade model, however, supported the original findings reported by Fry and Hale (1996).

Even though the developmental cascade model explains a significant proportion of the age-related variance in fluid reasoning, some studies have shown that there is remaining age-related variance that remains unexplained. For example, the Fry and Hale (1996) study showed that there was about 20% of the age-related variance that was unexplained by speed and working memory. These findings introduce the possibility that an additional variable could be included into the model to bring about complete mediation. Importantly, recent studies examining the role of working memory in fluid reasoning in adults have suggested the importance of the ability to retrieve information from secondary memory (e.g., Unsworth & Engle, 2007) as the key factor that determines why working memory predicts fluid reasoning.

Considering the research on the relationship between secondary memory and fluid reasoning in adults (Unsworth & Engle, 2007; Unsworth, Brewer & Spillers, 2009) and children (De Alwis, Myerson, Hershey, & Hale, 2009), it is reasonable to propose secondary memory as a candidate for the missing mediator that could account for the unexplained variance in the developmental cascade model. Moreover, even if the development of the ability to retrieve information from secondary memory is not the ONLY factor that is responsible for the development of fluid reasoning (i.e., developmental improvements in primary memory may also play a critical role), it is possible that both the development of working memory and secondary memory may directly influence the development of fluid reasoning. These two possibilities are depicted below in a modification of the original model used by Fry and Hale (1996) (see Figure 4)

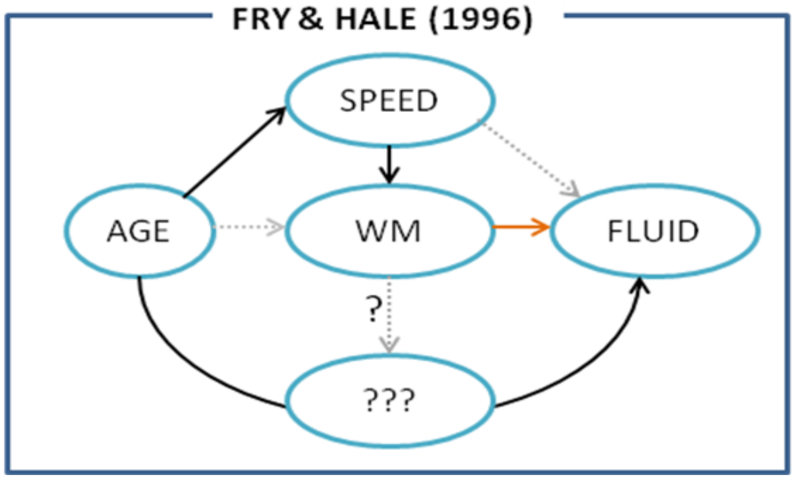


Figure 4. Schematic of a modification of the Fry and Hale (1996) model with an additional variable as the missing mediator.

Development of Primary and Secondary Memory

As discussed before, William James (1890) first proposed the division of memory into two systems. According to James primary memory refers to the current contents of consciousness, whereas secondary memory refers to memories that need to be brought back to consciousness through retrieval. This distinction between primary and secondary memory was carried forward in 1965 in Waugh and Norman's model. The current literature generally uses short-term memory (STM) and long-term memory (LTM) to refer to primary and secondary memory respectively. However, one of the critical ideas recently put forward by Unsworth and his colleagues (e.g., Unsworth, Spillers & Brewer, 2010) is that traditional working memory tasks may appear to measure both primary memory and secondary memory. For this reason, in the current study I will use the terms primary and secondary memory rather than STM and LTM.

Primary and secondary memory has been distinguished in many ways with the most important difference being the distinction in capacity. Primary memory is limited in capacity and there is a limitation in the number of items that can be maintained in conscious awareness at a particular time. The Miller (1956) suggestion of a 7 plus or minus 2 items has long been an accepted estimate of primary memory capacity. However, recent work by Cowan and colleagues suggest the capacity of primary memory may be limited to either 1 or 4 items (Cowan, 2001). In contrast to primary memory the capacity of secondary memory is not as limited as it represents any information relevant to the current task.

Primary and secondary memory can also be differentiated based on the neural substrates that support the two systems. Most of the evidence for this distinction has come from neuropsychological cases of amnesia. The classic case of patient HM has shown that damage to the hippocampus and surrounding areas of the medial temporal lobes cause deficits in retrieving long-term memories, but not short-term memories. (Milner, 1966). Patient KF, who had damage to the perisylvian cortex, showed an opposite pattern in which short-term memories for verbal material were disrupted where as long-term memories were intact (Shallice & Warrington, 1970).

Yet another difference between primary and secondary memory is the different types of processing used to store information in the two memory systems. Verbal items are most often coded phonologically in primary memory and semantically in secondary memory (Baddeley, 1966b; Craik & Levy, 1970). Also, surface features like visual or phonological characteristics help to maintain information in primary memory where as deeper levels of processing such as semantic encoding help with retrieving information from secondary memory.

Behavioral evidence for the primary and secondary memory distinction comes from serial position effects in list learning tasks. Typically in a list learning task, items from the end of the list (which are generally recalled first) are thought to be retrieved from primary memory while the early items are thought to be recalled from secondary memory (Waugh & Norman, 1965). Studies from adults and children have shown supporting evidence of this pattern of recall (Unsworth et al., 2010; De Alwis et al., 2009).

Working memory and its relationship with secondary memory

The Baddeley (2000b) model of working memory indicates that working memory is linked to long-term memory through the episodic buffer. Unlike the models of working memory proposed by Nelson Cowan and Klaus Oberauer; Baddeley describes the working memory system to be a separate entity from long-term memory. In contrast, Nelson Cowan, in his embedded process model, refers to working memory as an "activated portion of long-term memory" (Cowan, 1999). In the embedded process model the short-term store is simply the activated portion of long-term memory. Within the activated portion of the short-term store, the subset of items currently in conscious awareness is called the "focus of attention." According to Cowan, the maximum number of items that can be held in the focus of attention is four (see Figure 5).

Oberauer's (2002) model of working memory is similar to Cowan's in that he agrees with the view that working memory is an activated component of long-term memory. Oberauer disagrees with Cowan only in terms of the capacity of the focus of attention. According to Oberauer, the activated items are in a region of direct access, and within this region only one item is selected for processing by the focus of attention.

The recent dual-component model of working memory proposed by Unsworth and Engle (2007) also suggests a significant relationship between working memory and long-term memory. However, as mentioned earlier, they use the terms primary and secondary memory. According to Unsworth and Engle, working memory relies on both primary and secondary memory abilities. Primary memory consists of a simple storage component which can store about four items (which is similar to the concept of the focus of attention described by Cowan, 1999). Secondary (long-term) memory holds the items that have been displaced from primary memory when the capacity of primary memory has been exceeded.

Recent work by Unsworth, Engle and colleagues has focused on exploring the components of primary and secondary memory within working memory and also their relationship to fluid reasoning abilities. I will discuss some of these studies in detail in the following section.

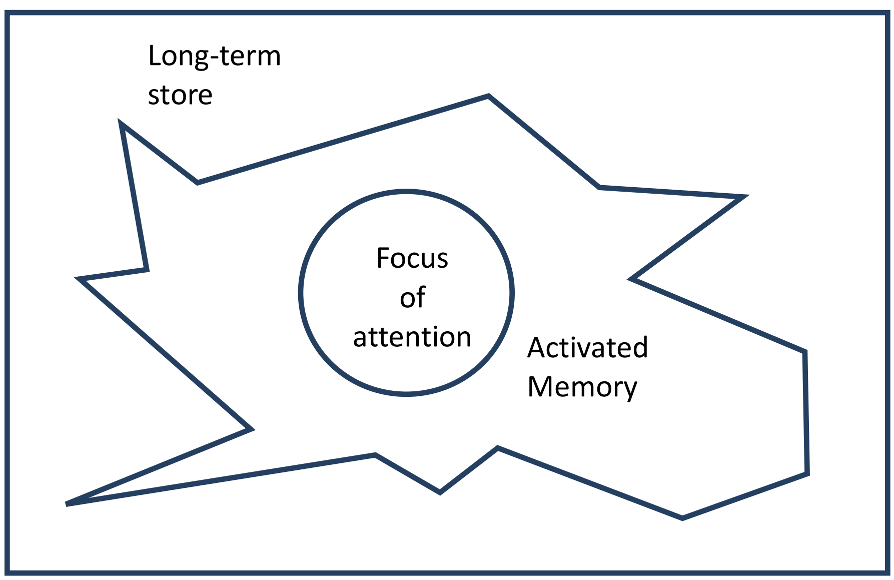


Figure 5. Schematic of the Nelson Cowan's embedded process model of working memory adapted from Cowan (1999).

Working Memory, Secondary Memory and Fluid Reasoning

A number of researchers have focused their work on gaining a better understanding of the link between working memory and fluid reasoning. In particular, Unsworth and Engle (2005) found that correlations between performance on the operation span task and the Ravens Advanced Progressive Matrices were relatively independent of the level of difficulty and memory load associated with specific reasoning problems. Working memory predicted performance on both high and low memory load problems. This led Unsworth and Engle to conclude that something other than the number of items that can be held in memory must account for the shared variance between working memory and fluid reasoning.

Salthouse and Pink (2008) conducted a similar study of adults ranging in age from 18 to 98 and reached the same conclusion. In this study, the researchers examined the correlation between working memory and fluid reasoning across different levels of difficulty (i.e., series length) in a working memory task. They found strong correlations with fluid reasoning even for the shortest series lengths of the working memory task, leading them to conclude that the relation between working memory and fluid reasoning is not dependent on the amount of information that needed to be maintained.

Unsworth and Engle (2006) further explored the underlying components that drive the relation between working memory and fluid reasoning. Their recent work suggests that the component of retrieving information from secondary memory is an important factor in the relationship. In particular, Unsworth and Engle (2006) proposed that different types of span tasks will engage primary and secondary memory components to varying degrees in different situations. For example, in complex span tasks such as reading span, participants are required to make judgments about sentences that are presented between items to be recalled. Because the secondary tasks require that participants temporarily switch attention away from maintaining items in primary memory, some of the to–be-remembered items must be retrieved from secondary memory. Therefore, Unsworth and Engle argued that complex working memory tasks always require the use of both primary and secondary memory. In contrast, simple span tasks (during which only maintenance is required) make use of the secondary memory component only when the to-be-remembered items exceed four items. Under such circumstances, some of the earlier items that have been displaced from primary memory need to be recalled from secondary memory.

To evaluate this hypothesis, Unsworth and Engle (2006) tested a group of younger adults on simple and complex working memory and fluid reasoning tests. The simple spans consisted of word and letter span tasks, and the complex span tasks consisted of operation span and reading span. The fluid reasoning tests were Raven's Progressive Matrices and the Matrix Reasoning subtest from the Wechsler Abbreviated Scale of Intelligence. Exploratory factor analysis revealed three distinct factors: simple spans with longer list lengths, simple spans with shorter list lengths, and complex spans. There was a strong correlation between the factors for simple spans with longer list lengths and complex spans but only moderate correlations between both of these factors and simple spans with short list lengths. In terms of fluid reasoning, simple spans with longer list lengths and complex spans were both better predictors of fluid reasoning than simple span with shorter list lengths. Overall, Unsworth and Engle concluded that retrieving information from secondary memory was an important predictor of fluid reasoning in adults.

In a more recent study, Unsworth, Spillers and Brewer (2010) explored the functions of the two components of primary and secondary memory within working memory . Their results revealed that the ability to maintain information in primary memory and the ability to retrieve information from secondary memory are two important components of working memory. In this study they tested a group of young adults between the ages of 18-35 on a battery of tasks that consisted of immediate free recall, working memory and fluid reasoning. Confirmatory factor analyses and structural equation models were used to identify the relationships among the constructs (i.e., the latent variables). Overall, the results supported a dual-component model of working memory indicating that working memory consisted of both primary and secondary memory components. This conclusion was based on the fact that their results revealed that both primary and secondary memory components accounted for unique variance in working memory.

Mogel, Lovett, Stawaski, and Sliwinski (2008) suggested that secondary memory was a better predictor of fluid reasoning than working memory. In their study, participants were tested on multiple measures of processing speed, working memory, secondary memory, and primary memory. They used the Raven's Progressive Matrices test as the single measure of fluid reasoning. Structural equation modeling was used to fit the data and the results showed that secondary memory accounted for a unique variance over and above what was accounted for by working memory.

In contrast, recent work by Unsworth, Brewer and Spillers (2009) showed that both the ability to retrieve information from secondary memory and the ability to maintain and manipulate information in working memory are important predictors of fluid reasoning in young adults. They analyzed data from participants between ages of 18 to 35 years who were tested on multiple measures of working memory, secondary memory and reasoning tasks. Structural equation modeling suggested that both working memory and secondary memory were related to fluid reasoning, and accounted for both shared and unique sources of variance in fluid reasoning.

A recent reanalysis of data from McCabe et al. (2010) supported the above results by directly comparing working memory and secondary memory as predictors of fluid reasoning in adults between the ages of 18 to 90 years. The working memory battery included three complex verbal span tasks while the measures of secondary memory were taken from the California Verbal Learning Test (recall of the first 12 items from trial 1, the last learning trial, recall after the distracter list and recall after a 30 minute delay). An exploratory factor analysis revealed two principle components with eigenvalues greater than 1.0, establishing working memory and secondary memory as separate abilities. When working memory and secondary memory were compared as predictors of performance on Raven Advanced Progressive Matrices, both were predictive to a similar degree. Regression analyses showed that working memory accounted for a significant proportion of the variance in fluid reasoning over and above the variance explained by secondary memory. Similarly, secondary memory accounted for a significant proportion of the variance in fluid reasoning over and above the variance explained by working memory. These results suggest that working memory and secondary memory both predict unique as well as shared variance in fluid reasoning in adults.

Shelton, Elliot, Matthews, Hill, and Gouvier (2010) proposed a slightly different view. In their study, too, participants completed multiple measures of speed, working memory, secondary memory, primary memory and fluid reasoning tests. Structural equation modeling indicated that working memory accounted for unique variance in fluid intelligence whereas the variance explained by secondary memory was shared with working memory. The lack of consistency among these three studies clearly underscores the importance of determining how these constructs ultimately predict fluid reasoning.

In the developmental literature, the role of secondary memory as a predictor of fluid reasoning has not been fully investigated. In a recent study I explored the relationship between a fluid reasoning task and immediate and delayed recall in 57 children, ages 6 -16 (De Alwis, Myerson, Hershey & Hale, 2009). In this study, we tested the hypothesis that retrieval from secondary memory is predictive of fluid reasoning in children. Participants were tested repeatedly on the free recall of a supra-span list (Children's Memory Scale). Their fluid reasoning ability was assessed using the Woodcock-Johnson III Spatial Relations subtest. Immediate recall of the first 10 (pre-recency) items of the 14-word list was assumed to measure retrieval from secondary memory, and selective effects of proactive interference validated this interpretation. Consistent with Unsworth and Engle's (2006, 2007) two-component theory, children's immediate recall of pre-recency items predicted both age and individual differences in performance on a test of fluid reasoning and shared the variance accounted for by delayed recall.

Although De Alwis et al. (2009) study provides evidence for a relationship between secondary memory and fluid reasoning in children, the constructs of working memory, secondary memory, and fluid reasoning have not been examined in a single study in children. Therefore, the aim of this study is to examine working memory and secondary memory as competing predictors of fluid reasoning in children and consider secondary memory is a plausible candidate for the missing mediator that might account for the variance in fluid reasoning that is unexplained by the developmental cascade.

RATIONALE AND HYPOTHESES FOR THE CURRENT STUDY

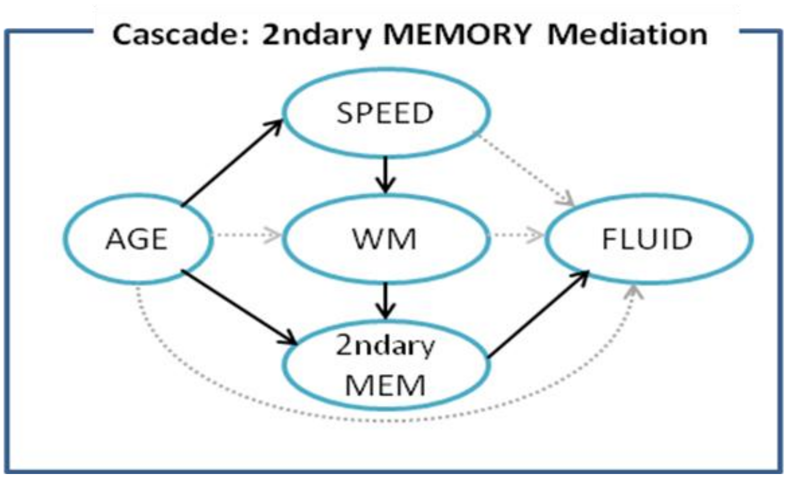
Summarizing the research thus far, the following conclusions can be made:

1. Working memory is a significant predictor of fluid reasoning in adults and children.
2. The developmental cascade model (Fry & Hale, 1996) shows that age-related improvements in speed and working memory lead to improvements in fluid reasoning.
3. The evidence concerning how much of the variance in fluid reasoning in children is explained by the development of speed of processing and working memory is inconsistent.
4. The dual-component model of working memory (Unsworth & Engle, 2006) suggests that improvements in secondary memory may account for residual variance in the developmental cascade model.
5. In children, it has been found that the ability to retrieve information from secondary memory is correlated with fluid reasoning (De Alwis, Myerson, Hershey & Hale, 2009).
6. The relations among working memory, secondary memory and fluid reasoning have not been examined in a single study in children.

The main goal of this study was to evaluate the effects of age-related differences in speed, working memory, and secondary memory on age- related differences in fluid reasoning. More specifically, I examined the developmental cascade model including secondary memory as a variable in order to find out if age-related improvements in secondary memory account for the age-related variance in fluid reasoning that is not accounted for by speed and working memory.

Hypothesis 1:

Age- related improvement in working memory influences fluid reasoning indirectly via its direct influence on the development of secondary memory.

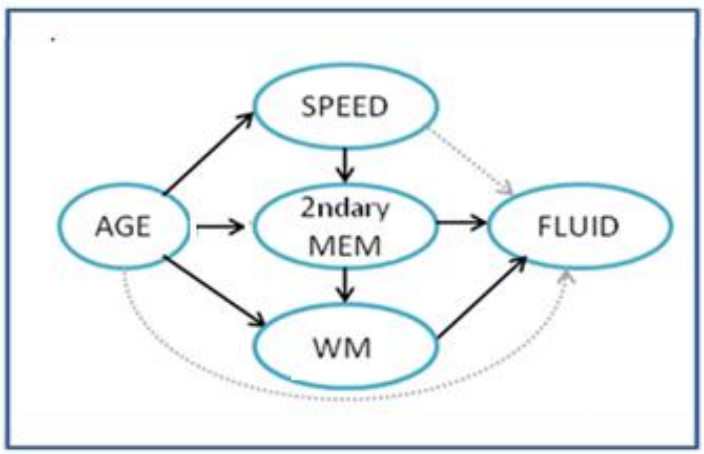


The figure shown above is an adaptation of the developmental cascade model proposed by Fry and Hale (1996). As discussed above, according to the cascade model the relations between speed and fluid reasoning is mediated by working memory. Mogel et al. (2008) suggests secondary memory to be a better predictor of fluid reasoning compared to working memory in young adults. In children too there is evidence for secondary memory to be related to fluid reasoning (De Alwis et al., 2009). These findings indicate secondary memory to be an important predictor of fluid reasoning. As suggested by Mogel et al., if secondary memory is a better predictor of fluid reasoning than working memory, it is possible that working memory influences fluid reasoning indirectly via its direct influence on the development of secondary memory. If this is the case, then the path from working memory to reasoning will not be significant, but the path from working memory to secondary memory and the path from secondary memory to fluid reasoning will be significant.

Hypothesis 2:

Age-related improvements in working memory and age-related improvements secondary memory both have direct effects on fluid reasoning and improvements in secondary memory mediate the improvements in working memory.

working memory and 2ndary memory mediation



The figure shown above is another adaptation of the Fry and Hale (1996) developmental cascade model. As discussed above, according to the cascade model working memory mediates the relations between speed and fluid reasoning. Unsworth and colleagues claim that both working memory and secondary memory account for both shared and unique sources of variance in fluid reasoning. Therefore, it could be assumed that both working memory and secondary memory will independently influence fluid reasoning. If this is the case, then the two paths from working memory and secondary memory to fluid reasoning will be significant.

Also, unlike in the original cascade where speed influences working memory, the above model assumes that secondary memory mediates the relation between speed and working memory. This change in the model is based on the findings of Unsworth, Spillers and Brewer (2010) who claim secondary memory to be an important component within the working memory system. If secondary memory contributes to the performance of working memory, then it is possible for secondary memory to mediate the relationship between speed and working memory rather than the relation between working memory and fluid reasoning.

METHOD

Participants

One hundred and twenty six children, aged 6-12 years participated in the current study. Children were recruited from public and private schools in the St. Louis County. All students from a particular grade within the schools were invited to participate in the study, and all who wished to participate were tested. Informed consent by the parents of participating children was obtained prior to testing. Parents also completed a general information and health questionnaire (see Appendix A). Children received $10 per hour for their participation in the form of gift cards from the Boarders book store.

Procedure

Participants were tested in two sessions approximately one week apart. Each session of testing began with the administration of a list learning task, followed by two speed of processing tasks. Thereafter participants completed a working memory task which was followed by a final measure of fluid reasoning. The presentation of tasks was consistent across all children. Each testing session lasted from 45 minutes to an hour. Participants were tested individually with breaks between tasks.

Apparatus

All computerized tasks were programmed in E-prime 1.1 (Psychology Software Tools, Pittsburgh, PA) and presented on a 14 inch lap top computer. Responses for the speed of processing tasks were made by pressing two colored keys on an external keyboard. All other responses were made verbally and were recorded by the experimenter.

Speed of Processing Measures

Four speed of processing tasks were presented in the battery. Samples of the processing speed tasks are shown in Figure 6

Animal Judgment Task. In this task, on each trial participants were presented with two black and white line drawings of an animal and an object (see Figure 6a). The task was to identify the animal as quickly and accurately as possible by pressing the corresponding left/right keys. If the animal was on the right side of the screen they pressed the "/ key" and the "z- key" if the animal was on the left side of the screen. Participants made their responses on an external keyboard and the response keys were covered by colored stickers. Participants completed 10 practice trials followed by 20 test trials. Decision reaction times were recorded in milliseconds by the computer program.

Size classification Task. This task required participants to make judgments about the size of circles. On each trial two colored circles were presented on either side of the computer screen. One of the circles was bigger than the other (see Figure 6b). The task was to identify the bigger circle as quickly and accurately as possible by pressing the corresponding left/right keys. If the bigger was on the right side of the screen they pressed the "/ key" and the "z- key" if the bigger circle was on the left side of the screen. Similar to the previous task, participants made their responses on an external keyboard and the decision reaction times were recorded in milliseconds by the computer program. Participants completed 10 practice trials followed by 20 test trials.

Rotation Task. In this task participants saw line drawings of objects on either side of the computer screen. One of the objects was in the upright position while the other was upside down (see Figure 6c). The task was to identify the upside down object as quickly and accurately as possible by pressing the corresponding left/right keys. If the upside down picture was on the right side of the screen they pressed the “/ key” and the “z- key” if the upside down picture was on the left side of the screen. Similar to the previous tasks, participants made their responses on an external keyboard and decision reaction times were recorded in milliseconds by the computer program. Participants completed 10 practice trials followed by 20 test trials.

Visual Search Task. The visual search task required participants to scan two arrays of circles and find the array of circles that contained the target item which was a blue circle. All other circles in the array were presented in orange (see Figure 6d). The task was to identify the array of circles with the target blue circle as quickly and accurately as possible by pressing the corresponding left/right keys. If the array with the blue circle was on the right side of the screen they pressed the “/ key” and the “z- key” if the array with the blue circle was on the left side of the screen. Similar to the previous tasks, participants made their responses on an external keyboard and the decision reaction times were recorded in milliseconds by the computer program. Participants completed 10 practice trials followed by 20 test trials.

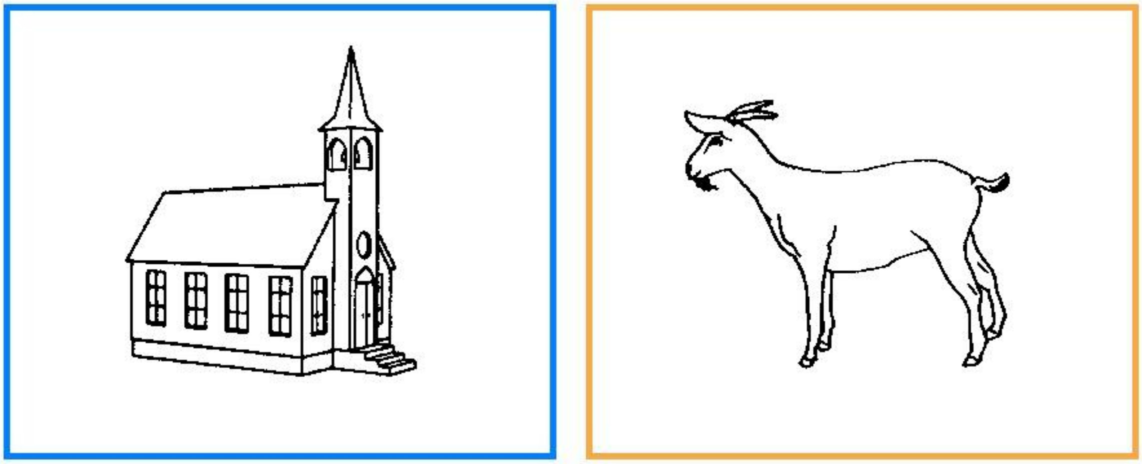


Figure 6a. Sample problem from the animal judgment task

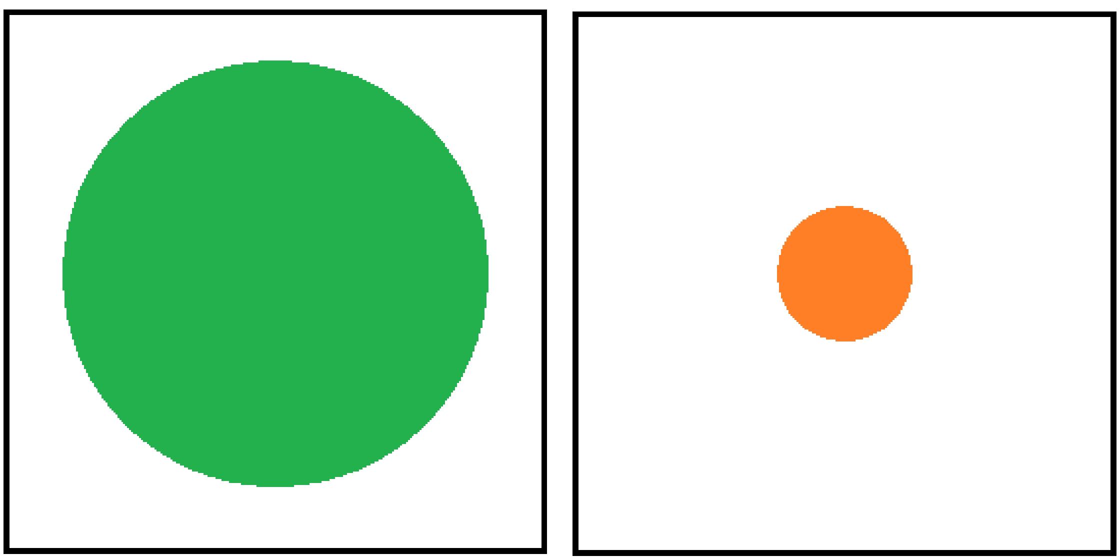


Figure 6b. Sample problem from the size classification task.

Figure 6. Sample of speed of processing tasks

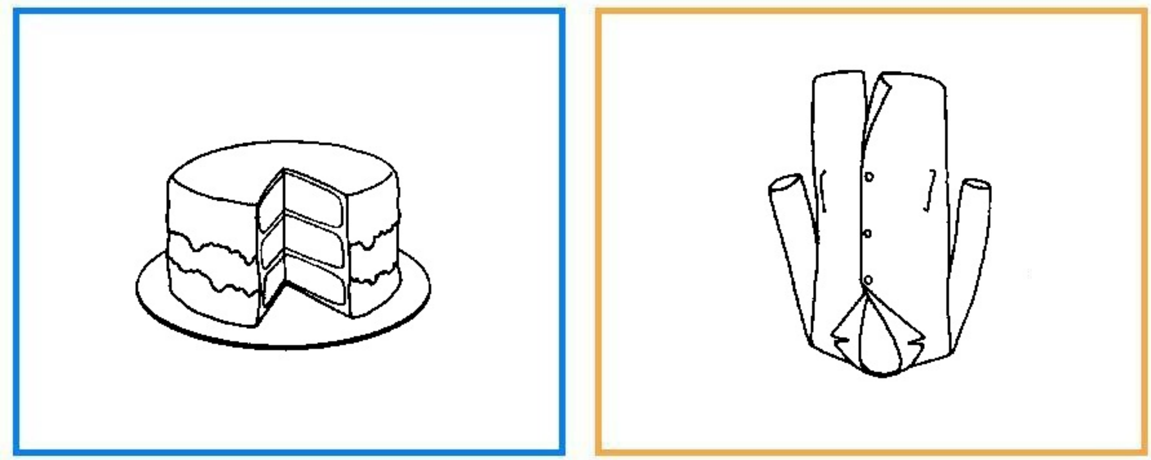


Figure 6c. Sample problem from the rotation task

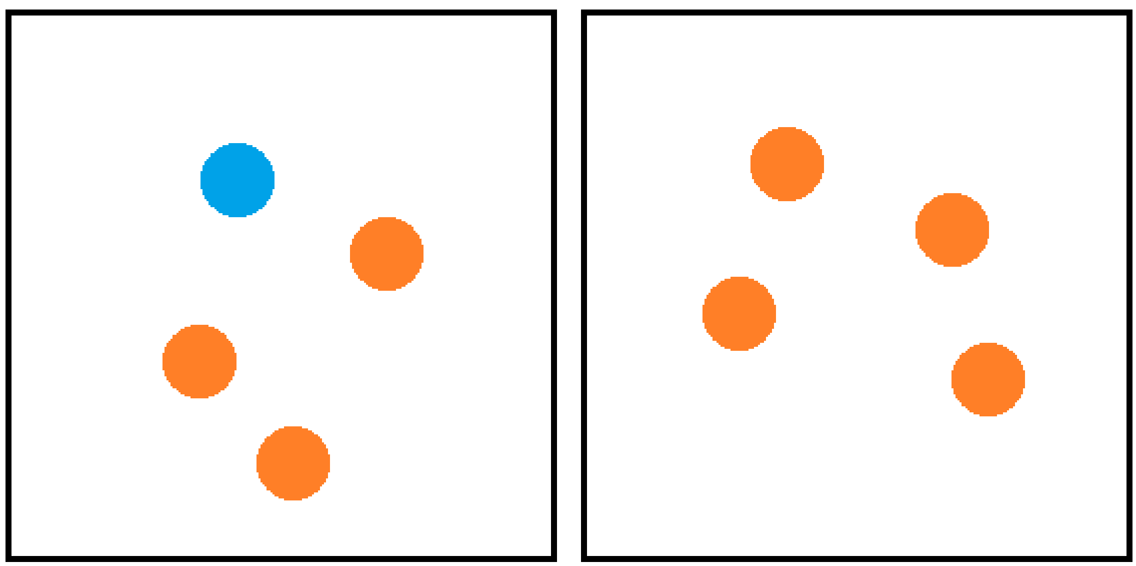


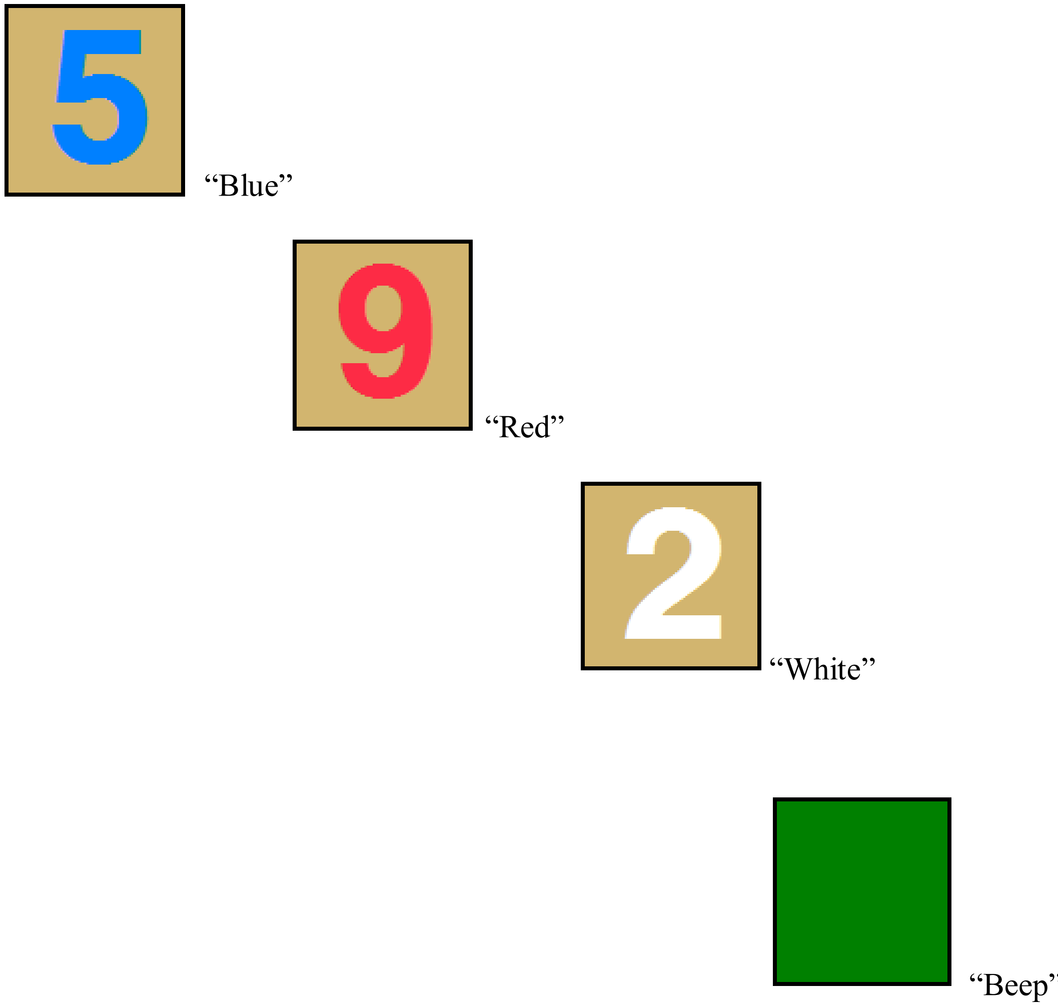
Figure 6d. Sample problem from the visual search task

Figure 6. Sample of speed of processing tasks

Working Memory Measures

Color Span. This working memory span task was adapted from Fry and Hale (1996). In this task participants were shown a series of digits ranging from one to nine. Each digit was randomly presented in red, white or blue in the middle of a white screen. As each digit was presented participants were asked to report the color of the digit. At the end of the series, they were asked to recall the digits in the same order in which they were presented. (Schematic of the color span task is presented in Figure 7). Considering the nature of verbal interference (reporting the colors of the digits while maintaining their identities in working memory) this task is considered to be a reliable assessment of verbal working memory (Hale, Myerson, Rhee, Weiss & Abrams, 1996). The series lengths were presented in ascending order beginning with a series length of two items and continuing to a series length of nine items. There were three trials in each series length and the task was discontinued if performance on all three trials within a series length was incorrect. Participants completed seven practice trials which were followed by the test phase. Feedback was provided during practice and additional practice was provided if the participant was not comfortable to proceed to the test phase. The longest series of items correctly recalled was considered to be the dependent measure and will be referred to as working memory span.

Each trial was initiated by a green fixation point which was followed by a blank screen of 500 ms. Thereafter the digits were randomly presented with each digit appearing on the screen for 3 seconds. At the end of the series a blank screen appeared for a 500 ms which was followed by a recall cue (a green square presented at the center of the screen accompanied by a beep). Participants reported the digits and the experimenter recorded the answers. The experimenter pressed the mouse to advance to the next trial.



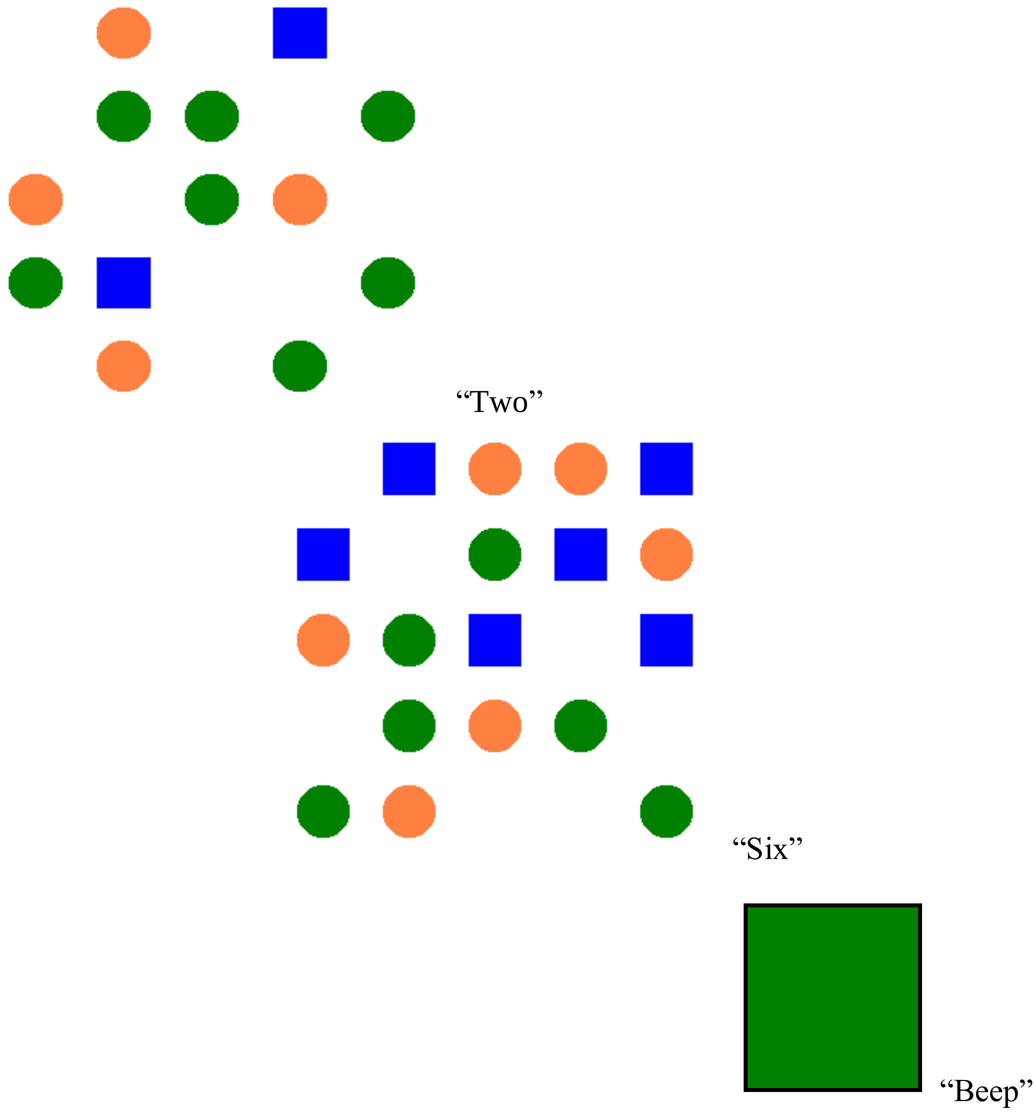
Correct Response: Five, Nine, and Two

Figure 7. Schematic of the color span task

Counting Span. This working memory task which was adapted from Alloway, Gathercole and Pickering (2006), is considered to be a reliable measure of complex working memory in children. On each trial participants saw an array of shapes. The shapes consisted of green circles, orange circles and blue squares. The task required participants to count the number of blue squares presented on each array and say the number. The number of squares on the array ranged from one to nine. The array of shapes was presented at the center of a blank screen and participants had as much time as they liked to count the squares. Participants pressed the space bar when they were ready to proceed to the next array of shapes. At the end of the series, participants were cued to recall the numbers in the same order in which they said them. (Schematic of the counting span task is presented in Figure 8).

The series lengths were presented in ascending order beginning with a series length of two items and continuing to a series length of nine items. There were three trials in each series length and the task was discontinued if performance on all three trials within a series length was incorrect. Participants completed seven practice trials which were followed by the test phase. Feedback was provided during practice and additional practice was provided if necessary. The longest series of items correctly recalled was considered to be the dependent measure and will be referred to as working memory span.

Each trial was initiated by a green fixation point and tone which was followed by a blank screen of 500 ms. Thereafter the arrays of shapes were randomly presented. At the end of the series a blank screen appeared for a 500ms which was followed by a recall cue (a green square presented at the center of the screen accompanied by a beep). The experimenter recorded the answers and pressed the mouse to advance to the next trial.



Correct Response: Two and Six

Figure 8. Schematic of the counting span task

Secondary Memory Measures

California Verbal Learning Test- Children's Version (CVLT-C). This test consisted of a list of 15words that could be categorized (see Appendix B). The categories were fruits, clothing, and toys. There were five learning trials. Children heard the list of words and were asked to recall the words in any order. The experimenter recorded the responses. In the standard administration of this test, after the fifth trial a distracter list is presented and thereafter the original list is recalled. For the purpose of this study, two speed of processing tasks were administered after the fifth trial and participants were asked to recall the original list thereafter (trial 6). (I did not use the distracter list because of the possibility of using the distracter list as a study list in a longitudinal follow up to this study). In addition, the standard administration of the test requires participants to recall the word list after a filled delay of 30 minutes which is followed by a cued recall test. For the current study I did not administer the cued recall test and the final free recall (trial 7) took place at the end of the testing session which was after about a 40-45 delay. The dependent measures for secondary memory were the recall after a short delay on trial 6 (recall from the trial after the speed of processing tasks were administered) and recall on trial 7 (the final free recall trial).

Children's Memory Scale (CMS) Word List Learning Task. In this task participants heard a list of fourteen random words (see Appendix C). On the first trial they heard all fourteen words which they recalled in any order. In the subsequent trials participants were selectively reminded of the words they missed. Thereafter they were asked to recall the list. In the standard administration of this task, at the end of the fourth trial participants hear and recall a different list of words (distracter list) and thereafter recall the original list. The original list is recalled once more after a delay of about 30 minutes.

For the purpose of this study participants performed two speed of processing tasks after the final learning trial (trial 4) and recalled the list of words thereafter (trial 5). They also recalled the list once again (trial 6) at the end of the testing session which was after about a 40-45 minute delay. (Again, I did not use the distracter list because of the possibility of using the distracter list as a study list in a follow up of this study). The standard administration of the test has a cued recall component which was not included in this study. The dependent measures for secondary memory were the recall after a short delay on trial 5 (recall from the trial after the speed of processing tasks were administered) and recall on trial 6 (the final free recall trial).

Fluid Reasoning Measures

WISC-IV Matrix Reasoning Subtest. The WISC-IV Matrix Reasoning subtest (Weschsler, 2003) requires participants to identify missing portions of patterns. For this study I used a computerized adaptation of this test. On each trial participants were shown an incomplete matrix with answer choices at the bottom of the screen. A problem similar to those presented in the WISC-IV Matrix Reasoning test is shown in Figure 9.

As each problem was presented, participants indicated their answer choice by pointing to the screen and the experimenter selected the answer choice by clicking the mouse. The matrix reasoning test consists of 35 test items, but for this study I used only the odd problems (18 test problems) because I hope to use the even problems in a follow up of this study. Participants had as much time as they needed to complete the test. The computer stopped the test if they got three incorrect answers in a row or three out of the last four answers incorrect. This stopping rule is not a standard part of the administration of this test, but because the items progress in difficulty, it seems reasonable that correct multiple-choice responses after a long series of failing to select the correct response would likely be due to guessing. Moreover, it is critical not to fatigue young children who are less likely to be able to correctly answer the most difficult items.

Raven's Standard Progressive Matrix Reasoning Test. The Raven's Standard Progressive Matrix Reasoning Test (Raven, Court & Raven, 1983) too requires participants to identify missing portions of patterns. I used a computerized adaption of this test as well. On each trial participants were shown a black and white pattern with a missing portion. Answer choices were presented at the bottom of the screen and participants were asked to indicate their answer choice by pointing to the screen. The experimenter selected the answer choice by clicking the mouse. A problem similar to those presented in the Raven's Standard Progressive Matrix Reasoning test is shown in Figure 10.

The standard progressive reasoning test consists of a total of 60 test items belonging to five sets (A-E) with 12 items each set (e.g. A1-A12). The items within a set become increasingly difficult. For the purpose of this study every third problem (Problems 1,3,6,9 and 12) within each set was used (25 test items total) in order to keep the number of test items parallel to WISC IV Matirx Reasoning. Participants had as much time as they liked to complete the test. As in the previous task and for similar reasons, the computer stopped the test if participants got three incorrect answers in a row or if three out of the last four answers were incorrect.

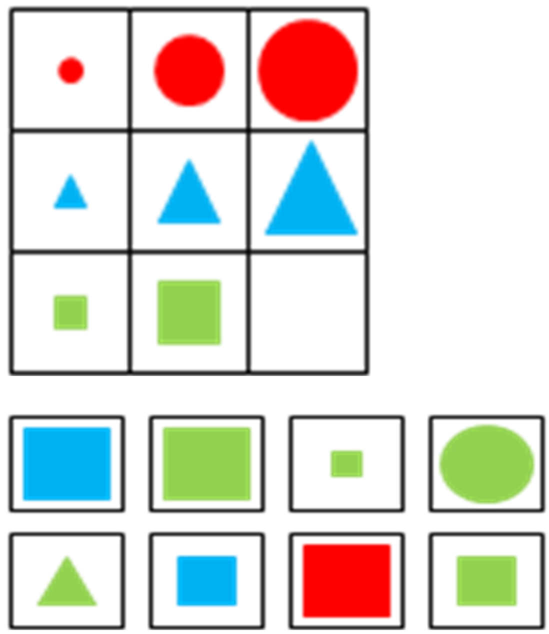


Figure 9. Schematic of a problem similar to that in the WISC- IV Matrix Reasoning Subtest

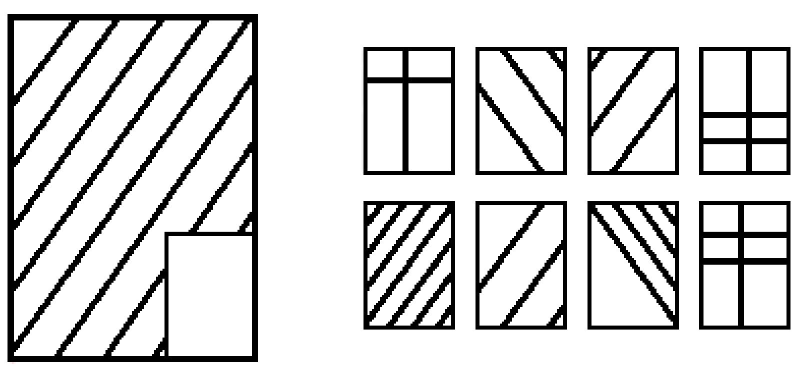


Figure 10. Schematic of a problem similar to that in the Raven's Standard Progressive Matrix Reasoning Test

RESULTS

Participant characteristics

A total of 126 children between the ages of 6-12 years participated in the study. Data from eleven participants were excluded from the analyses due to attention and learning disabilities and neurological disorders. Data from two participants (9 and 10 year old) were excluded due to high error rates on the processing speed tasks (i.e., 30% or higher error rate in at least one condition). Thus, data from 113 participants were analyzed in this study. Demographic characteristics of these participants are presented in Table 1.

Table 1

Demographic characteristics of participants

Age Group	N	Mean Age	% Female
6-8 years	44	7.56 (0.91)	45
9-10 years	40	9.96 (0.58)	58
11-12 years	29	11.80 (0.61)	45

Although age is treated as a continuous variable in this study, the participants have been divided into three groups in Table 1 in order to highlight the age and gender distribution. The means and standard deviations for all of the tasks and tests used to assess the various cognitive constructs (e.g., working memory) are presented in Table 2. The median reaction time scores are presented for the speed of processing tasks. The longest series of items correctly recalled (which is referred to as working memory span) served as the dependent measure for both working memory tasks. The mean scores from the delayed recall trials are presented for the CVLT-C and the CMS word list learning task, and the mean raw scores are presented for WISC- IV Matrix Reasoning Test and the Raven's Matrices. The inter-correlations between all of the cognitive variables and age are presented in Table 3.

Table 2
Descriptive Statistics for Cognitive Measures

Construct and Variable	Age Group		
	6-8 years	9-10 years	11-12 years
Speed of Processing*			
Animal judgment task			
Mean	698.04	562.92	468.52
SD	157.86	110.81	83.83
Rotation task			
Mean	1013.40	840.55	710.86
SD	264.68	152.78	102.27
Size classification task			
Mean	694.07	545.07	451.83
SD	148.94	85.26	60.75
Visual search task			
Mean	608.04	476.36	410.59
SD	145.17	68.10	60.25
Working Memory			
Color Span			
Mean	3.98	5.20	5.86
SD	1.22	1.14	0.99
Counting Span			
Mean	3.87	4.95	5.79
SD	1.34	1.15	1.32
Secondary Memory			
CVLT-C			
Trial 6			
Mean	8.73	11.85	11.90
SD	3.34	1.82	1.68
Trial 7			
Mean	8.91	11.98	11.59
SD	3.40	1.54	1.86
CMS			
Trial 5			
Mean	7.91	9.68	10.38
SD	2.79	2.23	2.07
Trial 6			
Mean	7.44	9.43	9.86
SD	3.18	2.59	2.23
Fluid Reasoning			
WISC Matrix Reasoning			
Mean	9.89	12.30	13.45
SD	2.63	1.56	1.92
Raven's Matrices			
Mean	11.47	15.25	17.21
SD	3.99	3.99	3.51

* Average median reaction times are provided for the speed of processing tasks.

Table 3

Intercorrelations between cognitive variables and age

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13
1 Age	--												
2Animal Judgment	-.676	--	.595	.531	.447	-.215	-.214	-.253	-.367	-.123	-.218	-.321	-.165
3 Size Classification	-.750	.797	--	.653	.654	-.258	-.209	-.391	-.407	-.222	-.294	-.236	-.166
4 Rotation Task	-.639	.733	.811	--	.682	-.054	-.051	-.303	-.334	-.182	-.280	-.133	-.003
5 Visual Search	-.735	.720	.844	.825	--	-.186	-.202	-.304	-.359	-.256	-.260	-.334	-.116
6 Color Span	.605	-.535	-.590	-.419	-.545	--	.476	.397	.349	.185	.203	.337	.248
7 Counting Span	.576	-.518	-.545	-.400	-.536	.658	--	.331	.339	.345	.362	.373	.337
8 CVLT_T6	.578	-.543	-.644	-.559	-.593	.607	.553	--	.806	.439	.435	.233	.239
9 CVLT_T7	.540	-.592	-.631	-.561	-.601	.561	.544	.866	--	.383	.422	.237	.223
10 CMS_T5	.475	-.400	-.485	-.426	-.502	.417	.522	.589	.540	--	.854	.203	.250
11 CMS_T6	.443	-.443	-.506	-.476	-.483	.413	.520	.574	.557	.884	--	.265	.220
12 WISC- MR	.645	-.617	-.603	-.491	-.647	.595	.604	.518	.501	.443	.467	--	.392
13 Raven's MR	.576	-.488	-.522	-.370	-.488	.510	.557	.492	.464	.453	.416	.616	--

Note. Correlations > .18 are significant at $p < .05$, correlations > .35 are significant at $p < .01$.
Correlations with age are presented below the diagonal and correlations with age controlled are presented above the diagonal

Assessment of Cognitive Variables

Assessment of the processing speed construct

Analyses of processing speed were based on median response times. Response times on each of the four speed tasks were significantly negatively correlated with age, indicating that speed of processing increased with age. All four measures were positively correlated with each other (*r*s ranging from .72 to .84). The skewness indices for three of the four speed tasks were greater than 1.0, and therefore a logarithmic transformation of response time was used. Given the strong intercorrelations between the four speed measures, an average z score of the four transformed response time scores was calculated and used in the correlation and path analyses. The reliability coefficient (Cronbach's alpha) for the composite speed score was .94.

Assessment of the working memory construct

Working memory was measured using the color span and the counting span tasks. The longest series in which all of the items were correctly recalled was used as the dependent measure for each task and will be referred to as working memory span. The longest series correct on the two tasks correlated significantly with each other ($r = .66$). Considering the strong correlation between the two working memory measures, a composite working memory score was calculated by first converting the results on each task to z scores and then calculating an average z score. This composite score was used in the subsequent correlation and path analyses. The skewness index for the working memory composite was less than one, and the reliability coefficient (Cronbach's alpha) was .79.

Assessment of the secondary memory construct

The secondary memory composite was calculated as the mean z score from four delayed recall trials, two from The California Verbal Learning Test –children's version (CVLT-C) and two from the Children's Memory Scale (CMS) word list learning task. For each task, the dependent measures for delayed recall from secondary memory were recall after a short delay (i.e., the recall trial after the speed of processing tasks) and the final free recall trial, at least 30 minutes later. The correlations between the four estimates of secondary memory ranged between .54 and .59.

The skewness index for the CVLT-C scores was greater than 1.0, and therefore an arcsine transformation was used to normalize the distribution. Even though the distribution of the CMS scores was not skewed, an arcsine transformation was used on the CMS scores as well in order to maintain consistency and also because transforming the data did not significantly change the distribution of the CMS scores. Because the CVLT-C and CMS measures were on different scales, each child's transformed scores were then converted to z scores and the average of the four z scores were used as a composite (i.e., the average of the z scores for CVLT-C trials 6 and 7 and CMS trials 5 and 6). The reliability coefficient of the composite score of secondary memory was a Cronbach's alpha of .86.

Immediate recall from secondary memory (i.e., not after a delay) also was calculated using the Tulving and Colatla (1970) method (The number of words between a given word's presentation and recall were calculated. If there were seven or fewer words intervening between presentation and recall of the particular word, the word was considered to be recalled from primary memory. If there were more than seven words, then recall was thought to be from secondary memory). However, this measure showed a relatively lower reliability coefficient of .51 (Cronbach's alpha). Therefore, only the delayed recall trials were used as estimates of secondary memory.

Assessment of the fluid reasoning construct

Fluid reasoning was measured using the Standard Raven's Progressive Matrices and the Matrix Reasoning subtest from the WISC- IV. For each test, the raw score of the total number of correct problems were calculated for each participant. As expected, Matrix Reasoning and Ravens Progressive Matrices were significantly correlated with each other (r = .62). Considering the strong correlation between the two measures, a composite fluid reasoning score was calculated. Because the two measures were on two different scales, each child's score on each measure was first converted to a z-score and the average of the two z-scores was used as the composite for fluid reasoning in the subsequent analyses. The reliability coefficient (Cronbach's alpha) of the composite score of fluid reasoning was .76.

Assessment of the relations between age and each of the cognitive variables

Because previous research has shown that the growth functions describing improvements in cognitive abilities are nonlinear (e.g., Fry & Hale, 1996, 2000; Kail, 1991; Kail & Ferrer, 2007) growth functions were analyzed as functions of the logarithm of age, and log age was used as a variable in calculating correlations as well as in regression and path analyses. The growth function for the processing speed construct is shown in Figure 11.As may be seen, composite speed scores decreased linearly as a function of log age, reflecting the fact that the response times on which the speed scores are based showed a negatively accelerated decrease with age (when age was not transformed). Similarly, as can be seen in Figure 12, the composite working memory scores also were a reasonably linear function of log age, although in this case, scores increased with age. The growth curves for secondary memory and fluid intelligence, shown in Figures 13 and 14, reveal that the composite scores for these constructs were also linear functions of log age.

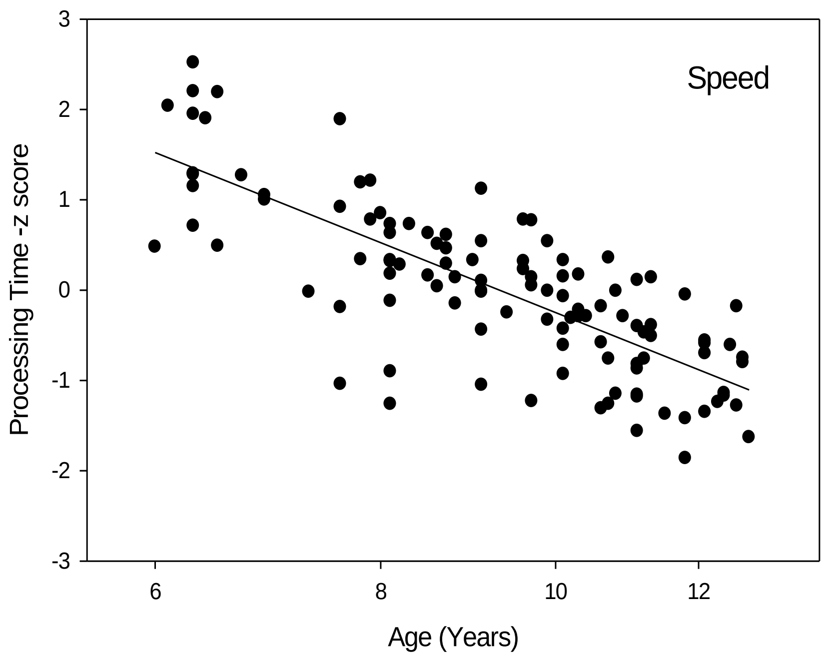


Figure 11. Growth functions depicting the linear decline of speed as a function of log age (note the logarithmic scale on the abscissa).

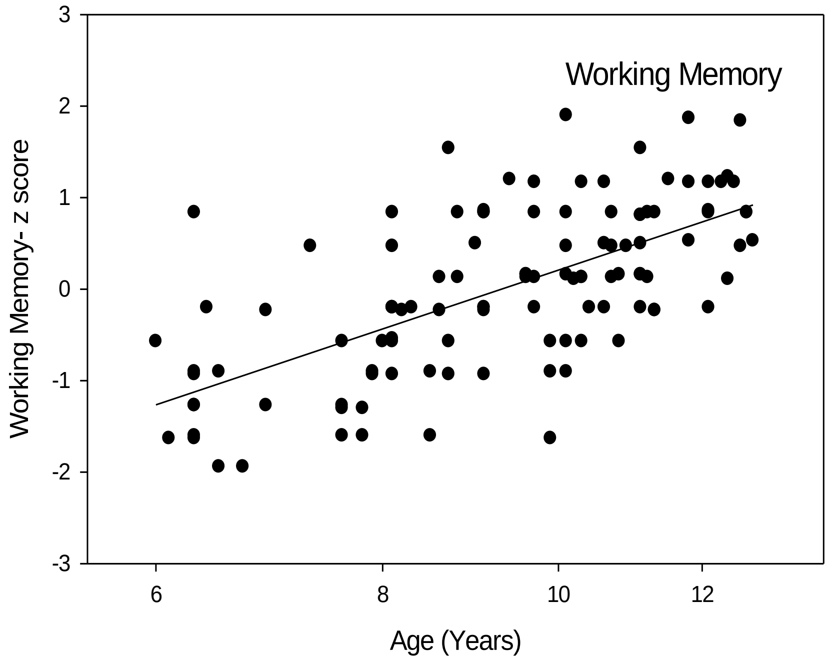


Figure 12. Growth function depicting the linear increase in working memory span as a function of log age (note the logarithmic scale on the abscissa).

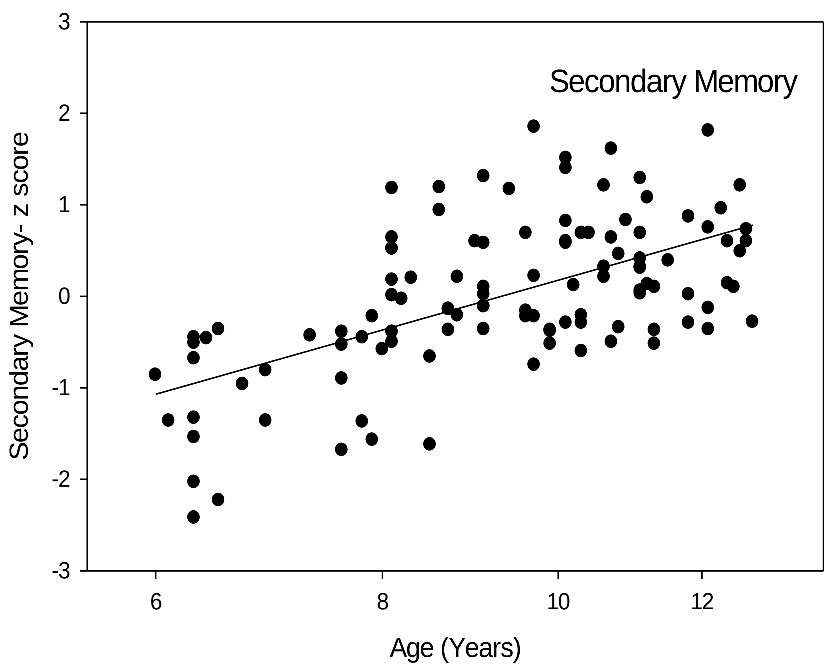


Figure 13. Growth function depicting the linear increase in recall from secondary memory as a function of log age (note the logarithmic scale on the abscissa).

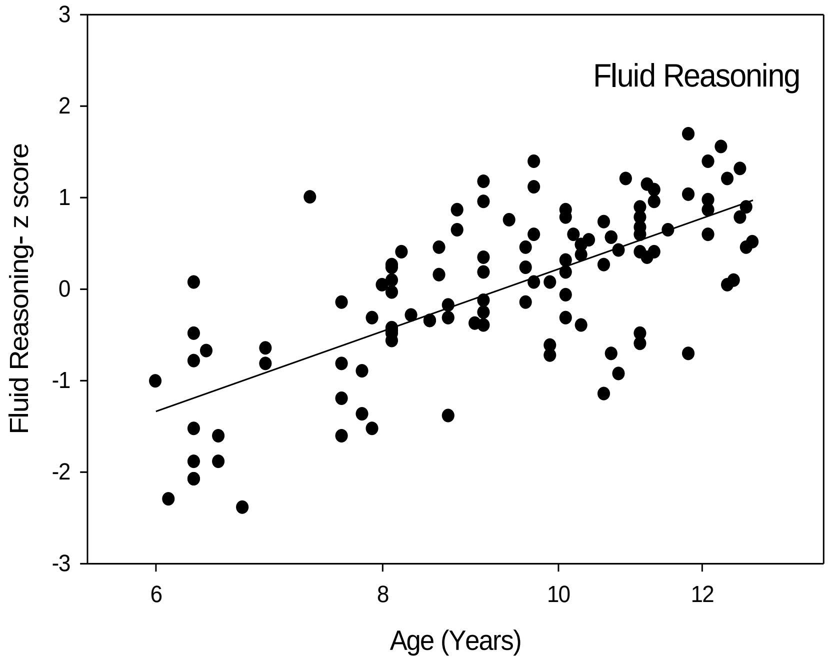


Figure 14. Growth function depicting the linear increase in fluid reasoning as a function of log age (note the logarithmic scale on the abscissa).

Correlational analyses

Table 4 shows the correlations between log age, and the logarithmically transformed z score composite of processing speed , the composite z scores for working memory and fluid intelligence, and the arcsine transformed z scores for the secondary memory composite. Table 5 shows the intecorrelations between all of the above variables after controlling for age.

Table 4
Intercorreltations between log age and composite scores

Measure	1	2	3	4
1 Log Age				
2 Speed	**–.774**			
3 Working memory	**.650**	**-.598**		
4 Secondary memory	**.596**	**-.585**	**.637**	
5 Fluid Reasoning	**.696**	**-.614**	**.692**	**.585**

Note. Bold correlations are significant at $p<.01$

Table 5

Intercorrelations between composite scores with age controlled

Measure	1	2	3
1 Speed			
2 Working Memory	**-.198**		
3 Secondary Memory	**-.242**	**.409**	
4 Fluid Reasoning	-.165	**.440**	**.296**

Note. Bold correlations are significant at $p<.05$

The correlations followed a pattern that was expected: Processing speed showed significant correlations with working memory, secondary memory and fluid reasoning, which in turn were significantly correlated with each other (Table 4). The pattern remained somewhat the same when age was controlled, although the correlations were reduced and the correlation between speed and fluid reasoning was not significant (Table 5). These results suggest that children's working memory and secondary memory predict both age and individual differences in performance on fluid reasoning tests.

Regression analyses

To explore the relations among these variables further and estimate the unique and shared contribution of each memory system to predicting fluid reasoning in children, multiple regression analyses were conducted. A hierarchical regression model was conducted with log age, working memory and secondary memory entered into the model at three steps. As may be seen in Table 6, secondary memory did not account for significant unique variance after age and working memory had been accounted for.

Table 6

Hierarchical regression of fluid reasoning on age, working memory and secondary memory

Predictor	R^2	ΔR^2	$F(\Delta R^2)$	*df*
Age	.478	.478	101.62*	111
Working Memory	.580	.102	26.86*	110
Secondary Memory	.589	.009	2.30	109

Note. * p <.01

Next, the order of entry of the memory variables was reversed, and secondary memory was entered into the model first, followed by working memory. The results, shown in Table 7, indicate that working memory contributes to significant unique variance in fluid reasoning after accounting for age and secondary memory.

Table 7

Hierarchical regression of fluid reasoning on age, secondary memory and working memory

Predictor	R^2	ΔR^2	$F(\Delta R^2)$	*df*
Age	.478	.478	101.62*	111
Secondary Memory	.525	.047	10.90*	110
Working Memory	.589	.064	16.99*	109

Note. * p <.01

Overall, a combination of age, working memory and secondary memory accounted for nearly 60% of variance in fluid reasoning. Age accounted for 48% of the variance, and working memory and secondary memory explained an additional 11%. Taken together, the results shown in Tables 6 and 7 indicate that working memory accounted for a unique 6.4% of the variance, and the variance explained by secondary memory was shared with working memory. Secondary memory by itself did not make a unique contribution to predicting fluid reasoning in children.

Path analyses

The main aim of the present study was to consider secondary memory as a possible mediator of age-related improvements in fluid reasoning in children and systematically explore the role of secondary memory within the context of the developmental cascade model. Path analysis was used to examine three potential mediators (speed, working memory, and secondary memory) of the relation between age and reasoning ability. Because testing one preferred model can be misleading, multiple comparative models based on different hypotheses were tested (MacCallum, 1995). The evaluation of the models was done by comparing fit indices. A Goodness of Fit Index (GFI) and an Adjusted Goodness of Fit Index (AGFI) of .95 or above, a non-significant chi-square, and an RMSEA value of .06 or lower were used as indicators of a good model fit (Thompson, 2000).

Developmental cascade model. The initial path analysis examined whether the current data replicated the Fry and Hale (1996) developmental cascade model (Model 1). The variables used for this model were log age and the composite scores for speed, working memory, fluid reasoning. According to the developmental cascade model (see Figure 15), age-related improvements in speed influence the development of working memory, and working memory directly influenced the development of fluid reasoning. Speed is assumed not to have a direct effect on fluid reasoning (as indicated by the light gray arrow). As expected, the model provided a very good fit to the data, with a nonsignificant chi-square and good fit statistics (see Table 8). When the direct path from speed to fluid reasoning was tested, it proved to be nonsignificant.

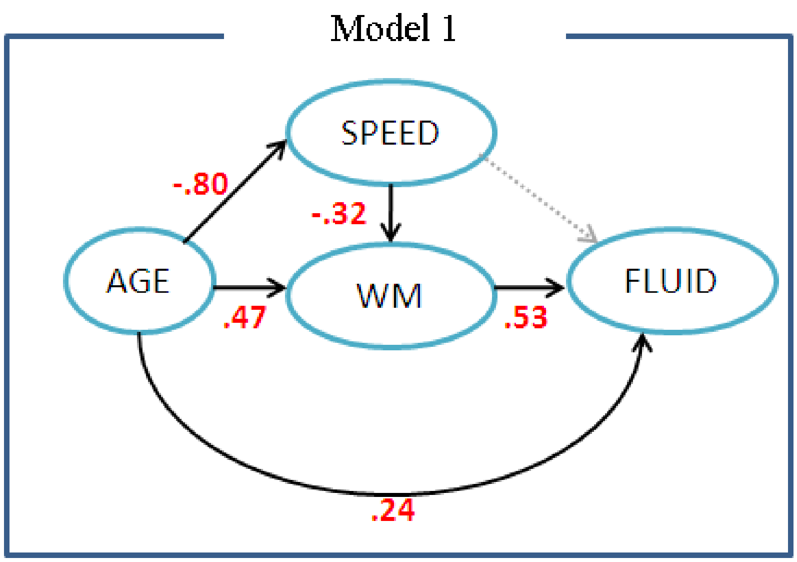


Figure 15. Developmental cascade model with path coefficients. The path from speed to fluid is set to zero. When this path was tested it proved to be non- significant.

Developmental cascade model with secondary memory. The next path model examined if a similar cascade can be observed when secondary memory was used as a substitute for working memory (Model 2). This model was based on evidence that retrieval from secondary memory is related to fluid reasoning in adults (Unsworth and Engle, 2006) and children (De Alwis, Myerson, Hershey & Hale, 2009). The variables used for this model were log age and the composite scores for speed, secondary memory, fluid reasoning. Similar to the developmental cascade model (see Figure 16), age-related improvements in speed influenced the development of secondary memory, and secondary memory directly influenced the development of fluid reasoning. Speed is assumed not to have a direct effect on fluid reasoning (as indicated by the light gray arrow). This model too provided a good fit to the data, with a nonsignificant chi-square and good fit statistics (see Table 8). When the direct path from speed to fluid reasoning was tested, it proved to be nonsignificant.

Model 2

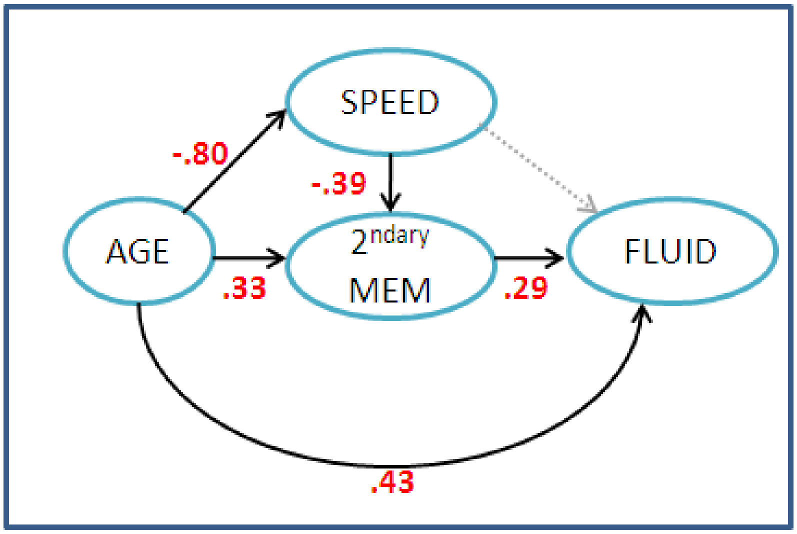


Figure 16. Developmental cascade model and path coefficients with secondary memory substituted for working memory. The path from speed to fluid is set to zero. When this path was tested it proved to be non- significant.

Comparing Model 1 to Model 2, it may be seen that the path from working memory to fluid reasoning is stronger than the path from secondary memory to fluid reasoning (.53 vs. .29). Also, there is a larger proportion of unexplained age-related variance in fluid reasoning in model 2 compared to model 1 (.43 vs. .24).

Hypothesis 1: Age-related improvement in working memory wields its influence on fluid reasoning indirectly via its direct influence on the development of secondary memory. Hypothesis 1 was based on Mogle et al.'s (2008) finding that in young adults secondary memory explained all of the variance in fluid intelligence accounted for by working memory as well as additional unique variance. If this is true, within a developmental context the age-related improvement in working memory wields its influence on fluid reasoning indirectly via its direct effect on the development of secondary memory. In this case, the path from secondary memory to fluid reasoning will be significant, and the path from working memory to fluid reasoning will not. The path model (Model 3a) and the path coefficients can be seen in Figure 17. The model provided a good fit to the data, with a non-significant chi-square and good fit statistics (see Table 8). Speed is assumed not to have a direct effect on fluid reasoning and secondary memory (as indicated by the light gray arrows) When the direct path from speed to fluid reasoning and speed to secondary memory were tested, they proved to be nonsignificant.

Moreover, when the non-significant paths were eliminated, the model (Model 3b, see Figure 18) continued to provide a good fit to the data (see Table 8). Even though the two models provided a good fit to the data, the models failed to support Hypothesis 1. This is because, as can be seen in Figures 17 and 18 the path coefficients from working memory to fluid reasoning in both Models 3a and 3b were significant while the paths from secondary memory to fluid reasoning were not, which is exactly the opposite of what was predicted by Hypothesis 1.

Model 3a

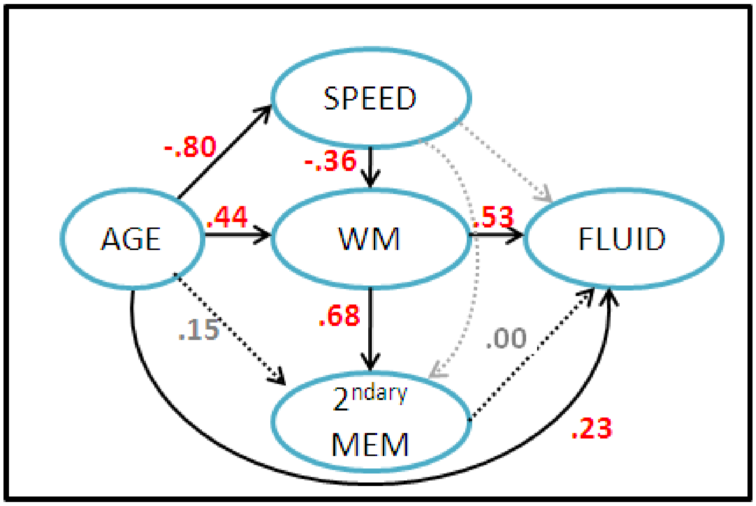


Figure 17. Path coefficients for the cascade model with working memory and secondary memory. The paths from speed to fluid and speed to secondary memory are set to zero. When these paths were tested they proved to be nonsignificant.

Model 3b

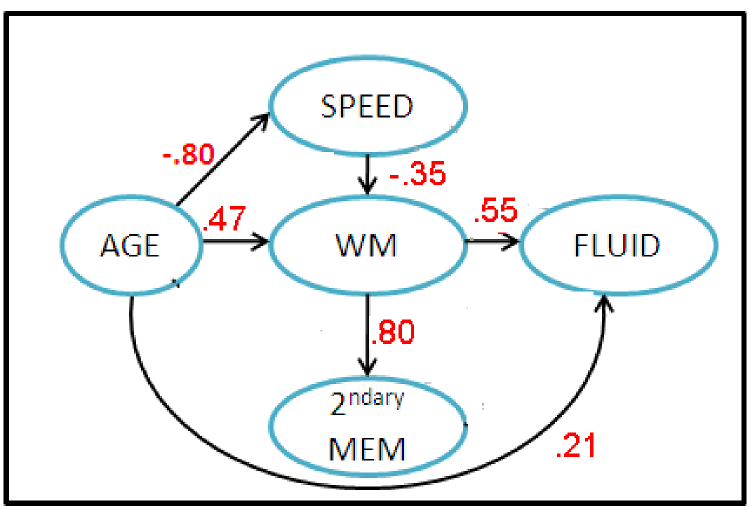


Figure 18. Path coefficients for the cascade model with working memory and secondary memory. All non -significant paths have been eliminated.

Overall, results related Models 3a and 3b suggests that when both secondary memory and working memory are introduced as predictors of fluid reasoning, working memory takes the role of being the key predictor explaining all of the variance accounted for by secondary memory as well as additional unique variance.

Hypothesis 2: Age related improvements in working memory and age related improvements in secondary memory both have direct effects on fluid reasoning and improvements in secondary memory mediate the improvements in working memory. Hypothesis 2 was based on Unsworth, Brewers and Spillers' (2009) finding that both working memory and secondary memory make unique contributions to predicting fluid reasoning in young adults. In this case both paths from working memory and secondary memory to fluid reasoning should be significant. Furthermore, secondary memory was expected to mediate the relationship between speed and working memory based on Unsowrth, Spillers and Brewers's (2010) claim that working memory relies on the two sub components of primary and secondary memory. In this case, the path from speed to secondary memory should be significant and the path from speed to working memory should not.

The path model (Model 4a) and the path coefficients can be seen in Figure19. The model provided a good fit to the data, with a non-significant chi-square and good fit statistics (see Table 8). Speed is assumed to not have a direct effect on fluid reasoning. The model continued to provide a good fit to the data with a non-significant chi-square and good fit statistics (see Table 8), when the non-significant paths were eliminated. Path model (Model 4b) and path coefficients can be seen in Figure 20. Even though Models 4a and 4b provided a good fit to the data, the models failed to support the idea that both working memory and secondary memory have direct effects on fluid reasoning. This is because, as can be seen in Figures 19 and 20 the path coefficients from working memory to fluid reasoning in both Models 4a and 4b were significant while the paths from secondary memory to fluid reasoning were not.

However, the results did support the idea that age related improvements in secondary memory mediate the improvements in working memory. As can be seen in Model 4a, the path between speed and secondary memory was significant while the path between speed and working memory was not.

Model 4a

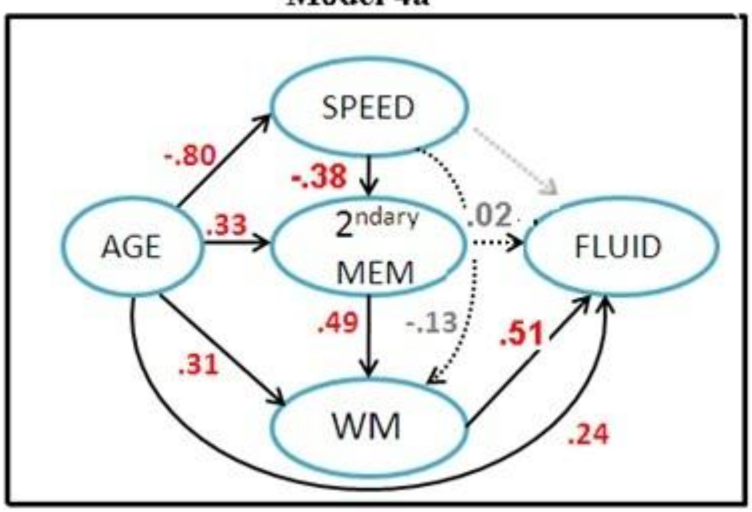


Figure 19. Path coefficients for the cascade model with secondary memory and working memory. The path from speed to fluid is set to zero. When this path was tested it proved to be non- significant.

Model 4b

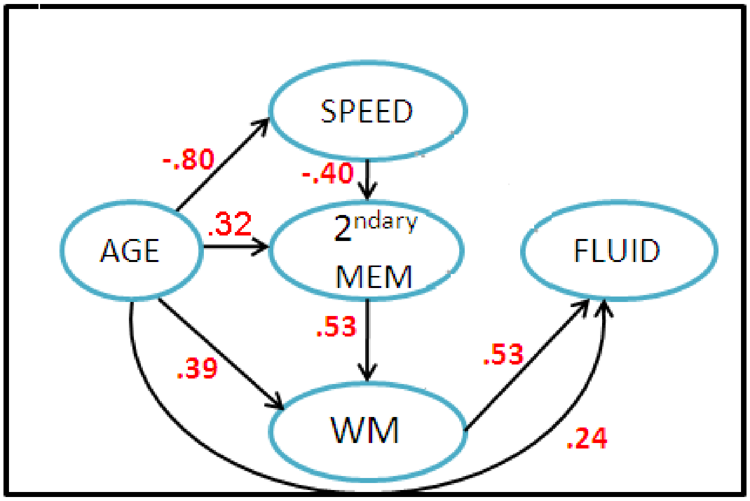


Figure 20. Path coefficients for the cascade model with secondary memory and working memory. All non-significant paths have been eliminated.

Overall, results related to models 4a and 4b indicate that secondary memory does not have a direct influence on fluid reasoning, but age-related improvements in secondary memory mediate the relations between speed and working memory

Table 8

Fit statistics for the path models

Model	Chi Square	*df*	*p*	RMSEA	GFI	AGFI
1	0.15	1	.669	<.001	.999	.993
2	0.79	1	.374	<.001	.997	.966
3a	1.89	2	.389	<.001	.993	.951
3b	3.30	4	.509	<.001	.989	.959
4a	0.13	1	.723	<.001	.999	.993
4b	1.16	3	.762	<.001	.996	.980

DISCUSSION

The primary aim of this study was to consider secondary memory as a possible mediator of age-related improvements in children's fluid reasoning abilities.
I wanted to systematically explore the developmental cascade model to determine if a large percentage of the age-related variance in fluid reasoning could be accounted for by speed, working memory, and secondary memory. Furthermore, this study was also focused on gaining a better understanding of the relationship between working memory and secondary memory and why working memory is generally such a good predictor of fluid reasoning in children (de Riabaupierre & Lecerf, 2006; Fry and Hale ,1996; Nettelbeck et al., 2010).

The results in the current study showed that children's speed of processing, working memory, secondary memory, and fluid reasoning abilities were all correlated with each other. This pattern of correlations remained somewhat the same when age was controlled (except the correlation between speed and fluid reasoning became non-significant) suggesting that children's working memory and secondary memory abilities predict both age and individual differences in fluid reasoning.

Regression analysis showed that a large amount of variance was shared between working memory and secondary memory. However, working memory contributed to significant unique variance in fluid reasoning and secondary memory did not. Path analysis supported the findings of the Fry & Hale's (1996) developmental cascade model indicating that working memory mediated the relations between speed and fluid reasoning. When secondary memory was substituted to the model for working memory, the model provided a good fit, but there was a larger proportion of variance in fluid reasoning that was unexplained. The path models exploring the relations between working memory, secondary memory and fluid reasoning indicated that working memory was the key predictor of fluid reasoning explaining all of the variance accounted for by secondary memory as well as additional unique variance.

Overall, the pattern of results indicated that secondary memory was not the missing mediator in the developmental cascade model. That is, when secondary memory was included as a variable in the path model, there was no direct path between secondary memory and fluid reasoning, and there was still a significant proportion of age-related variance in fluid reasoning that was unexplained.

However, these results did help to gain a better understanding of the relations among working memory, secondary memory, and fluid reasoning. More specifically, the present results were consistent with the claims of Unsworth and Engle (2006, 2007) who stated that the key to the relationship between working memory and fluid reasoning is the ability to efficiently retrieve information from secondary memory. The pattern of results in the path models showed that secondary memory did not have a direct effect on fluid reasoning, but influenced the process indirectly by mediating the relationship between speed and working memory. The best-fitting path models (Figures 19 and 20) showed that the efficiency and speed at searching and retrieving information from secondary memory to be an important aspect of the relationship between working memory and fluid reasoning. This pattern of results also supports the claims of Unsworth, Spillers and Brewer (2010) who showed primary and secondary memory to be two key components within working memory.

These results are also consistent with those of Shelton, Elliot, Matthews, Hill, and Gouvier (2010) who stated that working memory, but not secondary memory, accounted for unique variance when predicting fluid reasoning in a group of young adults. In children, too, there was shared variance between working memory and secondary memory, but only working memory accounted for unique variance in fluid reasoning.

Overall, this study contributes to the literature in several ways. To begin with, the present results replicated the findings of Fry and Hale (1996), thus providing further evidence supporting the developmental cascade model. Also, considering the recent work on the relation between secondary memory and fluid reasoning, this study showed that even though secondary memory and fluid reasoning were related, secondary memory is not as good a predictor of fluid reasoning as working memory. That is, the current results highlight the fact that there is something “special” about the working memory system; it is more than just retrieving information from secondary memory. More importantly, this study introduces a new cascade which includes the five constructs of age, speed, working memory, secondary memory and fluid reasoning. The pattern in this cascade shows that secondary memory does not directly influence fluid reasoning, but instead mediates the relation between speed and working memory.

Several recent research studies have focused on exploring the relations between working memory, secondary memory and fluid reasoning in young adults (Mogle et al, 2008, Unsworth, Brewer & Spillers, 2009; and Shelton et al. 2010), but the current study is the first to examine both working memory, secondary memory and their relation to fluid reasoning in children. As a result, the findings of the current study are of importance for the field of education as well as cognitive psychology.

As discussed before, recent work in cognitive psychology has focused on studying the relationship between working memory, secondary memory and fluid reasoning in adults. Even though these studies found that these three variables were related, the nature of the relations was not very clear. The results in the current study suggest that the efficiency and speed at searching and retrieving information from secondary memory may be an important determinant of working memory, and thus, indirectly, a predictor of fluid reasoning

In the area of education, many studies have explored the relationship between working memory and academic abilities such as mathematics (e.g., Swanson & Kim, 2007; St. Clair Thompson, & Gathercole, 2006), language comprehension (e.g., Kintsch, 1998; Cain, 2006; Gathercole & Baddeley, 1989), standardized test scores (e.g., Conway & Enlge, 1996) and other higher-order cognitive abilities like fluid and crystallized intelligence (e.g., Hutton & Towse, 2001, Fry & Hale, 1996; Swanson, 2008). All of these studies claim that working memory is closely associated with academic achievement.

Working memory is known to be a better predictor of academic abilities than specific executive abilities such as shifting, updating and inhibitory control (e.g., St. Clair -Thompson & Gathercole, 2006), although it has been hypothesized that the reason why working memory is a good predictor is because it involves executive abilities (e.g., Engle et al., 1999). Even though the role of executive functions was not the focus of the current research, I tested the relationship between semantic clustering (which is believed to be an executive ability) on the CVLT-C and fluid reasoning. The 15 to-be-remembered words from the CVLT-C can be categorized into fruits, clothing and toys. According to the

CVLT-C Manual, the ability to consecutively recall words from the same category is termed *semantic clustering* and is considered as an indicator of a child's ability to organize information. Semantic clustering or strategic response organization is generally thought to be an executive ability and is used in neuropsychological assessments of school-age children (e.g., Koren, Kofman, & Berger, 2005). Moreover, semantic clustering is known to allow efficient encoding and retrieval form secondary/ long-term memory (Craik, 1981). However, in this study the relationship between semantic clustering and fluid reasoning was not significant.

The results in this study suggest that secondary memory may partially underlie the influence of working memory on academic performance. In reading comprehension and tests of crystallized intelligence, retrieving information from secondary memory is important. Tests of crystallized intelligence measure learned knowledge, which must be retrieved from secondary memory. Reading comprehension also requires retrieving information, both crystallized knowledge and information acquired from the text, from secondary memory. Even on fluid reasoning and mathematical reasoning tests, retrieving information from secondary memory may be important. This is because partial solutions to a problem must often be displaced from primary memory to work on other parts of the problem, only to be retrieved from secondary memory later in order to construct the complete solution. According to the findings of the present study, the ability to efficiently search and retrieve information from secondary memory influences working memory performance which in turn influences fluid reasoning and educational abilities such as mathematical reasoning and reading comprehension.

Overall, however, the question remains as to why working memory is a good predictor of fluid reasoning in children and adults. There are several possibilities that have been explored over the years. One of the first hypotheses to be considered was related to working memory load. Carpenter, Just, and Shell (1990) suggested that individuals with higher working memory capacity perform better on fluid reasoning tasks like the Raven's Advanced Progressive Matrices (RAPM) because a larger working memory capacity is an advantage when problems require the manipulation of multiple rules. Recent studies, however, have failed to support an explanation related to working memory load. Unsworth and Engle (2005) showed that the relationship between working memory and fluid reasoning did not change significantly with the increase in the number of rules in RAPM problems. These findings indicated that the amount of simultaneous storage and processing (i.e., working memory load) is not a critical aspect that can explain the relationship between working memory and fluid reasoning.

A second line of reasoning was proposed by Engle and colleagues (Engle et al. 1999) who posited that the ability to control attention in the presence of distraction or interference is the underlying reason why working memory is predictive of fluid reasoning. More recent work by Unsworth and Engle (2007) further expanded on the controlled attention hypothesis. According to Unsworth and Engle, controlled attention plays a role in working memory tasks not only in the simultaneous storage and processing of information, but also in inhibiting interfering information and limiting the search set when retrieving information from secondary memory.

The ability to retrieve information from secondary memory and its relationship to fluid reasoning has been explored in studies of adults and children (Mogle et al, 2008;

Unsworth, Brewer & Spillers, 2009; and Shelton et al. 2010). In children, the ability to retrieve information from secondary memory is predictive of higher-order reasoning (De Alwis, Myerson, Hershey & Hale, 2009). However, the present results suggest that when secondary memory is measured independently of working memory, working memory remains the better predictor of fluid reasoning in children. These findings suggest that it is something other than the ability to retrieve information from secondary memory that makes working memory a good predictor of fluid reasoning in children.

This raises the question of whether the role of executive functions in working memory explains the relationship between working memory and higher-order cognitive abilities. McCabe et al (2010) tested a large group of adults between 18-90 years on an extensive battery of cognitive tests and concluded that the correlation between the latent constructs of working memory capacity and executive attention was so strong (r =.98) that they were possibly measuring the same thing. Furthermore, they suggested that this underlying executive attention construct was what was predictive of higher-order cognitive abilities in adults. When we re-analyzed the data from McCabe et al. (2010) looking at the relationship between working memory, secondary memory, and fluid intelligence, however, we found that both working memory and secondary memory each accounted for unique variance in predicting fluid intelligence (De Alwis, Myerson, McCabe, & Hale, 2010), suggesting that at least in adults, executive attention does not completely explain the role of secondary memory in individual differences in higher-order cognitive abilities.

Even though McCabe et al. (2010) show that executive functions and working memory account for a large proportion of shared variance in adults, in children we see a different pattern. St. Clair- Thompson and Gathercole, (2006), show that the relationship between working memory and academic abilities is stronger than the relationships of academic abilities to specific executive functions like inhibitory control, shifting, and updating.

Overall, the question of what makes working memory a good predictor of higher-order cognition remains unanswered particularly with respect to children. Finding a solution is important for both the children and adults though it is possible that the mechanism in adults might not be the same as that in young children. Some of the possible mechanisms that could be explored are discussed in the future directions section.

CONSIDERATIONS FOR FUTURE RESEARCH

A limitation of the current study is the relatively small sample size and the limited age range of 6-12 years. Increasing the age range will enable researchers to determine whether the relations among age, 6-12 years change in adolescence or whether the relations remain the same as those observed here.

Also, in this study the measures of working memory were limited to verbal span tasks, and the measure of higher-order reasoning was limited to fluid intelligence. Future studies should focus on using both verbal and spatial working memory tasks as well as other higher-order cognitive functions such as crystallized intelligence and measures of academic achievement in order to strengthen and clarify the relations among processing speed, working memory, secondary memory, and higher-order cognition.

In the area of cognitive aging, Hofer and Siliwinski (2001) have argued that cross-sectional studies over estimate the degree of association between processes (e.g., cognitive abilities) that change over time, and the same argument would hold for studies of cognitive development as well. Longitudinal studies, although they present other challenges, are free of this bias. In addition, they can provide information on within-individual change and both variation and covariation in age-related changes in different abilities. Whereas longitudinal studies are especially difficult to conduct on the effects of aging because of the amount of time involved, longitudinal studies of cognitive development are much more feasible and could add valuable information to our understanding. Accordingly, future research should examine the relations among speed of processing, working memory, secondary memory, and fluid reasoning using a longitudinal approach.

With respect to working memory and its relation to education, Alloway and colleagues claim working memory to be a better predictor of academic achievement than IQ (Alloway & Alloway, 2010). Also, working memory deficits have been found to be a characteristic of children with learning difficulties (Alloway, 2009; Alloway, Rajendran, & Archibald, 2009). It is possible that poor working memory performance in children with learning disabilities might be due to a difficulty in accessing information from secondary memory. The current findings suggest that this avenue of research may be particularly fruitful.

Recent work on working memory has focused on working memory training and its benefits for special populations of children. For example, studies of working memory training have been conducted with children with low working memory and children diagnosed with ADHD (Klingberg, Forssberg & Westberg, 2002; Holmes et al. 2009). Children with ADHD have difficulties with working memory (Barklay, 1997), academic performance (Alloway, Gathercole & Elliott, 2010), and retrieving information from secondary memory (Gibson, Gondoli, Flies, Dobrzenski & Unsworth, 2010). Imaging studies of children with ADHD indicate that they have an abnormality in the hippocampus, in that they show a larger hippocampal volume than normally developing children (Plessen et al. 2006). Children with diabetes who experience recurrent episodes of severe hypoglycemia also show larger hippocampal volumes compared to non diabetic sibling controls and diabetic children who do not experience three or more severe hypoglycemic episodes. (Hershey, Perantie, Wu, Weaver, Black & White, 2010). Because the hippocampus is associated with the formation of secondary/long-term memory, it may be important to further examine the relation between working memory and secondary memory in atypically developing children who are known to have structural and functional abnormalities in the hippocampal region of the brain.

With respect to the developmental cascade and the existence of age-related variance in fluid reasoning that is not explained by speed or working memory, there are some possibilities that can be can be considered. Recent research in young adults suggests that individual differences in complex associative learning predict performance in fluid intelligence (Tamez, Myerson & Hale, 2008). Another possible avenue stems from the fact that fluid tasks like Raven's Progressive Matrices involve both the abstraction and application of different rules. Thus, both complex learning and rule abstraction are variables that can be considered as potential mediators that might help to explain some of the remaining age-related variance in fluid reasoning in children. More importantly, however, another possible missing mediator that needs to be considered are the developmental changes in the brain, particularly the frontal cortex, that take place during childhood and adolescence (Goldman-Rakic,1987; Demspter,1992). The maturation of the frontal regions of the brain is associated with the development of executive functions (Conklin, Luciana, Hooper & Yager, 2007) that help with the performance on higher-order reasoning tasks, including fluid reasoning.(Ferrer, O' Hare & Bunge, 2009). Future studies involving both neuroimaging and behavioral measures are needed to further explore the possibility that underlying developmental changes in the frontal regions of the brain can account for age-related improvement in children's fluid reasoning.

In conclusion, the results in this study suggest that working memory is a better predictor of fluid reasoning in children than secondary memory. However, secondary memory plays an important role in the development of fluid reasoning by mediating the relationship between speed and working memory. These results in are helpful in understanding the nature of the relationship between children's processing speed, working memory, secondary memory and fluid reasoning. Recent research on cognitive development has been largely focused on the role of working memory in higher-order functions and educational attainment. The present results suggest that the development of secondary memory may be an important precursor to the development of working memory.

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APPENDIX A

04-111

* File in room 305B

Participant ID: __________________

GENERAL INFORMATION AND HEALTH QUESTIONNAIRE FOR CHILDREN

This information helps us to be sure that the children in our studies are similar in terms of background. If you are uncomfortable answering any question, feel free to discuss the question with the researcher or leave the answer blank.

Answers to the questions will not disqualify your child from participating in the study

PLEASE FILL IN THE BLANKS AND/OR CIRCLE THE APPROPRIATE ANSWER

PARENT/GUARDIAN INFORMATION

Parent/Guardian #1 Relationship to Child: ______________

Parent/Guardian #2 Relationship to Child: ______________

CHILD INFORMATION

Age: _____ Current Grade: _____ Race: ______________ Gender: MALE FEMALE

Is your child left or right handed? LEFT RIGHT

Is English your child's first language? YES NO

If NO, how old was your child when he/she learned English? _____

Does your child wear (or need to wear) glasses? YES NO

If YES, is vision corrected to 20/20? YES NO

Does your child wear a hearing aid? YES NO

Has your child ever been diagnosed with attention deficit disorder or a learning disability? YES NO

Please rank your child's health on the scale below from 1 to 7 where 1 is poor and 7 is excellent. Circle the appropriate number.

1	2	3	4	5	6	7
Poor		Fair		Good		Excellent

THANK YOU FOR TAKING TIME TO ANSWER OUR QUESTIONS!

APPENDIX B

California Verbal Learning Test- Children's Version (CVLT-C)

1. Bananas
2. Sweater
3. Puzzle
4. Jacket
5. Grapes
6. Blocks
7. Watermelon
8. Shorts
9. Crayons
10. Peaches
11. Balloons
12. Hat
13. Strawberries
14. Belt
15. Marbles

APPENDIX C

Children's Memory Scale (CMS) Word List Learning Task

1. Car
2. Forest
3. Dog
4. Night
5. Paper
6. Hand
7. Metal
8. Rock
9. Line
10. Window
11. Farmer
12. Watch
13. Sound
14. Bank