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The development of primary and secondary memory and their relationship to fluid intelligence

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THE DEVELOPMENT OF PRIMARY AND SECONDARY MEMORY AND THEIR RELATIONSHIP TO FLUID INTELLIGENCE

A Dissertation

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Agricultural and Mechanical College
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in

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“Let not mercy and truth forsake you; Bind them around your neck, write them on the tablet of your heart, and so find favor and high esteem in the sight of God and man. Trust in the Lord with all your heart, And lean not on your own understanding; In all your ways acknowledge Him, and He shall direct your paths.” Proverbs 3:3-6

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ABSTRACT

Researchers have been able to link working memory to many important cognitive abilities throughout the life span. Two of the unanswered questions about working memory are what cognitive processes function during working memory task performance and how do these processes directly relate to intelligence? A recent model (Unsworth & Engle, 2006) suggested that performance on working memory tasks was determined by two abilities: the capacity of primary memory and the ability to efficiently retrieve information from secondary memory. In the current study, we extended Unsworth and Engle's (2006) methodology to include two groups of children (ages 8-9 and 10-11). Our goals were to identify the developmental trajectory of primary and secondary memory and also to examine whether these abilities predict fluid intelligence in the same way that has been found in adults. By including scope of attention measures, which are theoretically similar to measures of primary memory, we were able to differentiate between Cowan et al.'s (2005) predictions concerning the relationship between primary memory and intelligence and Unsworth and Engle's (2006) findings regarding this relationship. Primary memory was higher in adults than in the child groups, but secondary memory did not have many differences between the age groups. We did not find strong support for Unsworth and Engle's (2006) model of primary and secondary memory in children, but we did show evidence that the scope of attention was an important predictor of intelligence and shared variance with working memory task performance in both the youngest age group and the adult group.

INTRODUCTION

We can probably all think of an instance in which we have to remember certain information, while also having to do something else. A common example is driving to a new location, where you must remember the name of the street that you need to turn on, while also surveying the road and traffic conditions. We also understand that some individuals are more capable of mastering these types of situations than others. In cognitive psychology, this ability to remember information while simultaneously processing information is referred to as working memory and the study of working memory has been ongoing since the first working memory model was published more than thirty years ago (Baddeley & Hitch, 1974). There is a large amount of research showing that performance on working memory tasks is predictive of numerous other cognitive abilities. Working memory capacity in adults is correlated with language processing abilities (Daneman & Carpenter, 1980), can predict performance on standardized aptitude tests (Turner & Engle, 1989), and is also a good predictor of fluid intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999). In children, working memory capacity has been shown to predict language development (Adams & Gathercole, 1996), as well as performance in the areas of English, mathematics and science as measured by the British national curriculum assessments in schools (Gathercole, Pickering, Knight, & Steggman, 2004).

Yet, one of the primary theoretical questions concerning working memory remains unanswered, that is, how do working memory tasks “work” in a way that makes them so useful of a predictor of other abilities? A common answer of leaders in this field has been that the strong relationship between higher order cognitive abilities and working memory performance is explained because both require the ability to control attention (Baddeley, 2007; Cowan et al, 2005; Engle, Tuholski et al., 1999). Having good control of attention is believed to improve memory in situations in which proactive interference is high (May, Hasher & Kane, 1999), when goal maintenance is necessary (Kane & Engle, 2003), when one must perform two different tasks simultaneously (Engle, Tuholski et al., 1999), or almost any time a specific cognitive skill is tested. However, direct evidence is lacking that supports this line of reasoning: working memory measures control of attention and control of attention is what links working memory performance to other higher-order cognitive abilities (Cowan et al., 2005).

In the current study, we have focused on what processes might be driving the relationship between working memory and fluid intelligence. The study of memory has been linked to the study of intelligence since the early intelligence tests were constructed (Hagen, Jongeward, & Kail, 1975). Intelligence is an important construct by itself because it has been shown to be a significant predictor of educational success, and career success (Strenze, 2007; Terman, 1940). In the current study, we chose to focus on fluid intelligence rather than intelligence as a whole or crystallized intelligence, because fluid intelligence is believed to be more representative of the core mechanism leading to individual differences in intelligence. It is also tested in a manner designed to be culture-fair, and does not penalize participants for lacking knowledge of the specific culture a “skills” test could be tailored toward (Cowan, 2005). Instead, fluid intelligence tests focus on abstract reasoning generally without any requirements for verbal skills. Because working memory tasks have been shown to be good predictors of fluid intelligence (Conway et al., 2002; Shelton, Elliott, Matthews, Hill, & Gouvier, 2010), exploration of the potential cause(s) of this relationship could provide methods for improving intelligence or for understanding the basic cognitive differences between individuals. Some researchers have already provided evidence that some children possess working memory deficits that cause them to perform poorly in school (Gathercole & Alloway, 2006). Thus, understanding the relationship between working memory and intelligence for these children could be vital to improving their likelihood of educational and career success later in life.

We conducted a developmental study based on a model of how working memory “works.” The theoretical model, provided by Unsworth and Engle (2006), states that working memory performance is determined by two processes: the capacity of primary memory and the efficiency of retrieval from secondary memory. The capacity of primary memory is believed to be the items that can be held in conscious thought, whereas, retrieval from secondary memory represents accessing items from long-term memory. Primary memory, importantly, has been defined similarly to the scope of attention (Cowan, 2001), which in the Cowan (2001) model is an important link between working memory performance and fluid intelligence. The current study was conducted with a developmental focus, using 8-9 year-old and 10-11 year-old age groups as well as young adults, to strengthen our analyses by providing more variability as compared to adult performance. Sometimes the range of adult performance on any given task is so small, most likely because it is based on a mature cognitive function that has certain boundaries or capacity limits, that it can limit the researcher’s ability to show relationships between that performance and some other task. Children, on the other hand, often show much wider variability, because their cognitive mechanisms are not fully mature and development can be slower or faster based on the individual. Therefore, using a developmental design allowed us to examine how other cognitive mechanisms, like rehearsal, impact primary memory, secondary memory and the scope of attention, three theoretical processes involved in working memory. We were also able to make developmental comparisons with our adult sample to replicate and extend the Unsworth and Engle (2006) model and the findings from their adult sample.

The Evolution of Working Memory

When Baddeley and Hitch (1974) published the first model of working memory, the study of short-term memory was in vogue (Baddeley, 2007, preface). Short-term memory is the type of memory that could hold small amounts of information for around 2 seconds, if a person is not permitted to continually rehearse the information (Baddeley, Thompson, & Buchanan, 1975). Working memory quickly took the place of short-term memory because working memory models could more easily account for previous findings that the simpler short-term memory models could not account for as easily. Additionally, the early working memory tasks showed predictive abilities that were not matched by short-term memory tasks (Daneman & Carpenter, 1980). These early tasks (counting span, Case, Kurland, & Goldberg, 1982; reading/listening span, Daneman & Carpenter, 1980; operation span, Turner & Engle, 1989) reflected the essence of working memory because they required participants to process the presented information (counting items, comprehending a sentence, or performing a mathematical operation) and to store information (number of total items counted, last word of the sentence or a presented letter/word) until the end of a series of alternating processes and presentations of to-be-remembered items, when serial recall was required. These tasks, often called storage-and-processing tasks, were reflective of the model that Baddeley and Hitch (1974) proposed.

In the Baddeley and Hitch (1974) model, storage-only tasks could be performed by one of two separate storage systems, which were differentiated by the type of information to be remembered. One system, the phonological loop, consisted of a store and an articulatory sub-vocal rehearsal mechanism. The loop was responsible for storing auditory information and for converting visual information into a verbal code if possible, and then storing that information in a similar manner to auditory information. The other storage system, the visuospatial sketchpad, also included a store and a rehearsal mechanism designed for pictorial or spatial information like maps or complex shapes. Much less research has been done on the visuospatial sketchpad so it is not known exactly what type of rehearsal is utilized (Logie, 1995). The third part of the original 1974 model was the central executive. The central executive was in charge of allocating attention to the current problem and to manipulation of the information in the two storage systems. In relation to the storage-and-processing tasks, the central executive was active in both processing of information and placing the to-be-remembered items into the correct storage system. Baddeley later introduced the episodic buffer as an additional storage system designed to incorporate information from the other two storage systems and from long-term memory (Baddeley, 2001). The episodic buffer has not been studied to the same extent that the other two storage systems have but it does show promise in its ability to explain how complex span tasks are performed and how information from long-term memory is utilized to assist short-term memory capacity.

Since this system has been developed, many researchers have called for a less modality specific model of working memory, mostly because of the belief that modality-specific storage systems are not necessary to explain why certain tasks do not interfere with one another (see Miyake & Shah, 1999; Ricker, Cowan, & Morey, 2010). Cowan’s (2001) nested framework model is a prominent example of such a model. This model of working memory stated that memory consists of items in the focus of attention, items in activated long-term memory, and the items stored in inactive long-term memory. The process begins with sensory memory activating items from long-term memory or creating a new representation for new items, which move to the fringe of consciousness. If some items are selected, then their representations are pulled into the focus of attention, which is the center of consciousness. The focus of attention is capacity-limited at about 4 chunks (at maximum capacity, the focus of attention is referred to as the scope of attention), but this limit varies slightly based on individual differences. Items can only be kept in the focus of attention through strategic processes, such as rehearsal. When the number of items in the focus exceeds capacity or when attention is not maintained on the items, some or all of the items leave the focus to return to the activated portion of long-term memory. The scope of attention in the model is the key contributor to the relationship between fluid intelligence and working memory. Engle, Kane, and Tuholski (1999) also describe a working memory model that includes activated information from long-term memory interacting with controlled attention, but more similarly to Baddeley and Hitch (1974) they predict the existence of numerous domain-specific codes, like the verbal or spatial codes used by the phonological loop or visuospatial sketchpad.

All of the models discussed place emphasis on the importance of controlled attention in working memory task performance. The researchers that proposed these models have also stated their belief that the primary reason that these tasks predict intelligence task performance is because performance on both tasks relies on the ability to control attention (Baddeley, 2007; Cowan et al., 2005; Engle et al., 1999). Controlled attention is believed to be especially important to fluid intelligence because the fluid intelligence tasks commonly require the participant to make several manipulations in one's mind or remember several key sub-steps involved in a procedure. These mental work-outs theoretically require high levels of attentional control so that steps are not missed and the whole task can be completed without succumbing to distraction present in the environment. However, this "control of attention hypothesis" has not yet been strongly supported by experimental research. Cowan et al. (2005) directly point out that, "it is far from clear how the storage-and-processing (working memory) tasks are carried out, what aspects of the tasks relate to aptitude, and whether all such working memory tasks operate similarly" (p. 44).

Alternatively, a model proposed by Conway and Engle (1996) but further updated by Unsworth and Engle (2006) has utilized a different approach to explaining the relationship between working memory and fluid intelligence. Their proposal was built on the assumption that performance on working memory tasks is actually the combination of two independent processes: the capacity of primary memory and the ability to accurately retrieve information from secondary memory (terms originally coined by James, 1890). The capacity of primary memory described the number of items (about 4 in adults; Cowan, 2001) that can be held in conscious thought at one time, like remembering the items you need to get on a quick trip to the grocery store. Secondary memory, or long-term memory, holds unlimited information from the past, but retrieval from secondary memory is dependent on search cues that may not be efficient, making the likelihood of recalling items from secondary memory lower than recalling items in primary memory. The search process used during retrieval from secondary memory is limited by the build-up of proactive interference, problems in how the information was encoded, and interference from possible but incorrect responses at test (Unsworth & Engle, 2007a). For example, if you met an old classmate in the mall, you might attempt to search secondary memory for where the individual sat in class to recall their name, but because this search cue is imperfect, you might instead mistakenly remember the name of the classmate that sat next to this individual. Unsworth and Engle (2007b) instead referred to maintenance in primary memory and a controlled cue-dependent search from secondary memory as the key processes involved during short-term memory and working memory tasks. These small differences in the phrasing surrounding the key constructs more accurately reflect the active nature of the constructs and specify what actions (maintenance/rehearsal or controlled searching, respectively) are required when an individual uses primary or secondary memory.

While this model was quite different from the model proposed by Baddeley and Hitch (1974), it shared several similarities with the nested processes framework proposed by Cowan (2001). Maintenance in primary memory worked very similarly to the focus of attention (Unsworth & Engle, 2007a) and primary memory, theoretically, had the same capacity as the scope of attention. Secondary memory was representative of both the activated and inactive portions of long-term memory, but retrieval from secondary memory was most dependent on the activated portions of long-term memory, because the items that were recently displaced from primary memory still maintain a high level of activation (Unsworth & Engle, 2006, 2007a). With the similarities in the models, but the differences in the predictions of the models in regard to the relationship between the scope of attention/primary memory with fluid intelligence, it was important to use the current study to directly test these hypotheses.

Historical Antecedents of Primary and Secondary Memory

While the current study focused on primary and secondary memory in the context of short-term and working memory tasks, a great deal of research on the topics of primary and secondary memory has been done in the past and it is important to understand the contributions and limitations of that body of work. Almost all of the previous work on primary and secondary memory involved a form of an immediate free recall test of a series of words or numbers (Watkins, 1974). Primary memory capacity was then believed to cause the unusually high levels of recall from the end of the list, known as the recency effect, whereas, memory recall for the rest of the list was caused by secondary memory efficiency.

One of the seminal articles dealing with the measurement of primary and secondary memory capacity was performed by Waugh and Norman (1965). Their goal was to create a specific theory for what processes caused forgetting in short-term memory. They believed that the distinction between primary and secondary memory was a key to understanding the different patterns of forgetting during immediate free recall tasks. Waugh and Norman stated that the primary memory mechanism explains recency performance because it has a sharply-limited capacity even though every item that is attended enters into primary memory. They also placed several conditions on items to exist in primary memory: new items will displace older ones when capacity is full, and displaced items are lost unless they are rehearsed enough before they are lost to be in secondary memory also; decay does not affect items in primary memory as long as they are rehearsed, but response-produced interference has a negative effect on items in primary memory as well as stimulus-produced interference. They developed a formula for measuring which items were likely in primary memory based on the number of new items presented since a certain item and the number of old items that have been recalled before the attempted recall of the certain item. This formula could be applied to any of the final seven words presented in the study list for immediate free recall. Using the formula for independent probability, total recall was predicted by: $R(\mathrm{i}) = P(\mathrm{i}) + S(\mathrm{i}) - P(\mathrm{i})S(\mathrm{i})$, therefore, the items in primary memory were: $P(\mathrm{i}) = [R(\mathrm{i}) - S(\mathrm{i})]/[1-S(\mathrm{i})]$. $P(\mathrm{i})$ represents the probability that an item is in primary memory, $R(\mathrm{i})$ represents the probability that a certain item will be recalled, and $S(\mathrm{i})$ represents the probability that an item is in secondary memory. The conditions that Waugh and Norman placed on primary memory are similar in many respects to the conditions that Unsworth and Engle (2006) outlined for primary memory in its relationship to working memory performance.

Waugh and Norman (1965) were able to demonstrate in several ways that primary memory, represented by superior recency performance, was distinct from secondary memory, represented by poorer pre-recency performance. While other researchers disagreed that there were two different memory stores, they also had to incorporate the findings that recency and pre-recency items were recalled differently (Tulving & Patterson, 1968). Quite a few researchers of this era found different manipulations, such as word frequency or acoustic similarity, which affected one of the memory systems but not the other, again demonstrating their independence (Craik & Levy, 1970; Kintsch & Buschke, 1969; Ellis, 1969; Waugh & Norman, 1968). One issue that arose was the proper measurement of the capacity of primary memory (Craik, 1968; Raaijmakers, 1982; Watkins, 1974).

Watkins (1974) reviewed the research on primary memory and he compared the different popular methods used to measure primary memory. At the time, the three major conceptualizations of primary memory were as a distinct storage mechanism (Waugh & Norman, 1965), as a representation of consciousness (Craik & Lockhart, 1972), and as a limited-capacity retrieval process (Tulving & Patterson, 1968). According to Watkins, each of these conceptualizations had flaws and current knowledge at the time was not sufficient to truly know which of the three was most accurate. The current thought about "what primary memory represents" is still not completely settled. Unsworth and Engle (2006) definitely refer to primary memory as a type of storage mechanism. However, the Cowan (2001) model, which includes the scope of attention that is similar to primary memory, states that these representations are held in the center of attention or simply the center of consciousness.

Watkins (1974) also described and compared several popular methods for calculating the capacity of primary memory. Although he described a total of six different techniques, he focused on four of these techniques for his analysis of each method's validity. The four techniques he selected to highlight include the Waugh and Norman (1968) method, a modified version of the Waugh and Norman (1968) method that corrects the possible underestimation of primary memory capacity by the original method, the Tulving and Patterson (1968) and the Tulving and Colotla (1970) method. The Waugh and Norman (1968) method has been described previously and the primary difference in the modified Waugh and Norman formula is the inclusion of the term that represents the probability of recalling the final item in the list (Rf). Watkins believed that the Waugh and Norman (1968) method underestimated primary memory capacity so by including the probability of the final item being in primary memory, he included a way to measure that items actually entered into primary memory. It is represented as: $P(\mathrm{i}) = R\mathrm{f}[R(\mathrm{i}) - S(\mathrm{i})]/[R\mathrm{f}-S(\mathrm{i})]$. Tulving and Patterson (1968) simply calculated the capacity of primary memory as any recalled item that had been presented in the final four positions in the list and secondary memory was any recalled item that had been presented before those final four positions, with the total list lengths typically being between 12 and 20 items. Tulving and Colotla (1970) refined this method by including output interference before concluding that any item had truly been recalled from primary memory. Typically in this method, an item is determined to be recalled from primary memory if fewer than 7 items have intervened between the item's presentation and recall. In both of the Tulving methods, any item recalled that is not from the final presented items is considered to be an item recalled from secondary memory.

Watkins (1974) then applied these four techniques to a large dataset from an immediate free recall experiment. He compared the variances for primary memory capacity across the 18 different conditions for each of the four techniques and found that the Waugh and Norman (1965) technique and the modified Waugh and Norman technique had much larger variances, representing less reliability, than the Tulving and Patterson (1968) or the Tulving and Colotla (1970) techniques. Then Watkins compared the ratios of secondary to primary memory capacities using an analysis of variance (ANOVA) to ascertain how well the particular technique was able to differentiate reliably between primary and secondary memory. He found once again that the Tulving techniques were superior to the Waugh and Norman technique with the Tulving and Colotla (1970) technique providing the best estimates of primary and secondary memory capacity.

The research on primary and secondary memory drastically declined after the Atkinson and Shiffrin (1968) model of memory gained popularity, which was also soon over-shadowed by the fast-growing popularity of the Baddeley and Hitch (1974) model of working memory. The Atkinson and Shiffrin (1968) model did draw from the distinction between primary and secondary memory by having two components of their model, the short-term store and long-term store, which served a similar purpose in memory to primary and secondary memory, respectively.

The Developmental Study of Primary and Secondary Memory

The primary goal of the current study was to examine primary and secondary memory development in children as measured by working memory and short-term memory tasks rather than by immediate free recall tasks. However, previous developmental research on primary and secondary memory using immediate free recall tasks was important for predictions of performance in the current experiment. A good deal of the past developmental research on primary and secondary memory examined trends in the later years of life rather than childhood. Craik (1968) performed an experiment with older (60-69 years-old) and younger adults (18-30 years-old) using four different types of stimuli: digits, English county names, animal names, and unrelated words. He utilized three different techniques to calculate primary memory capacity: the Murdock method, the Modified Murdock method, and the Waugh and Norman (1965) method. In each case, he estimated secondary memory by subtracting primary memory capacity from the total recall. His estimates were extremely variable across the three methods and he found significant differences in the primary memory capacity between the different categories of word lists. However, Craik concluded that primary memory was not significantly different between the two age groups but that secondary memory was significantly different between the two age groups, suggesting that primary memory capacity is resilient to age-related changes but that secondary memory declines with increasing age.

Other researchers examining differences in primary and secondary memory in older adults as compared to younger adults have likewise found that primary memory processes do not seem to change but secondary memory does decrease in later adulthood (Craik, 1977). When examining the reaction time to search primary versus secondary memory, primary memory differences are caused by a consistent age-related slowing but secondary memory differences indicate that there is an additional age difference slowing down the responses of older adults (Anders & Fozard, 1973; Coyne, Allen, & Wickens, 1986; Waugh, Thomas, & Fozard, 1978). Although the belief that there are not age differences in primary memory capacity has reached somewhat of a consensus, Parkinson, Lindholm, and Inman (1982) used the capacity measurement techniques of Tulving and Patterson (1968) and Tulving and Colotla (1970) and they did find significant age declines in capacity for both primary memory and secondary memory in their sample of older (58-89 years old) and younger (18-24 years old) adults. This suggested that primary memory could be more sensitive to age differences because the findings from researchers who utilized the Waugh and Norman (1965) formula did not find age differences, but those who utilized the techniques of Tulving and colleagues (1968, 1970) found age differences.

While there is a considerable amount of data regarding development of primary and secondary memory in later adulthood, there is not as much concerning changes in the capacity of primary and secondary memory in childhood. Dempster (1985) stated that short-term memory span and the recency effect did not show large developmental increases, possibly indicating that primary memory is not an important predictor of developmental differences. In addition, he stated that pre-recency and supraspan list lengths (those greater than span lengths with perfect recall) in short-term memory tasks show much larger age differences, indicating that secondary memory is likely developing during childhood. However, only one study examining primary and secondary memory capacity in children could be identified. Foos, Sabol, Corral, and Mobley (1987) performed a life-span study of primary and secondary memory capacity development. Their participants included an 8-12 year-old group, an 18-32 year-old group and a 60-79 year-old group. Participants immediately recalled a single list of 15 words and then the authors used the Tulving and Patterson (1968) and modified Waugh and Norman (1965) (modified by Watkins, 1974) techniques to estimate primary and secondary memory capacity for each of the three age groups. Foos et al. (1987) found that for both methods the children and the older adults had significantly poorer primary memory estimates than the young adults, but the older adults had significantly poorer secondary memory estimates than the children or the young adults, which did not differ. Obviously, this single experiment consisting of a single trial for each participant was not the strongest possible test for developmental differences between primary and secondary memory but it did support the findings of Parkinson et al. (1982) of a decline in primary memory in older adulthood. This experiment contradicted the statements of Dempster that primary memory is constant across childhood development and secondary memory increases greatly across childhood development.

A recent child study of primary and secondary memory was conducted by De Alwis, Myerson, Hershey, and Hale (2009). While they did not include actual estimates of primary and secondary memory, they were inspired to assess the claim of Unsworth and Engle (2006) that secondary memory was a larger predictor of fluid intelligence than primary memory when assessed with short-term memory and working memory tasks using a child sample rather than adults. Their participants were between 6 and 16 years old and they performed an immediate and a delayed free recall task as measures of primary and secondary memory and a spatial reasoning task to measure fluid intelligence. They did not find age differences in the likelihood of recall for the final four words of the list, indicating that primary memory was invariant. Secondary memory, as calculated as recall of the first four items presented in the list, did have a significant main effect of age, with older children recalling more of these items. They found significant correlations between recall from the middle of the list and the spatial reasoning performance, replicating Unsworth and Engle's (2006) finding that retrieval from secondary memory is related to fluid intelligence. These findings also support Dempster's (1985) claims for the development of primary and secondary memory in childhood. From these sparse studies on the development of primary and secondary memory in childhood, there is some evidence that primary memory does increase with increasing age and some evidence that it does not and there is some evidence that secondary memory increases with age and some evidence it does not. This lack of consensus further increases the need for more research examining the development of these two constructs in childhood.

Measuring Primary and Secondary Memory in Children

In the current experiment, we wished to examine primary and secondary memory capacity in children and young adults based on performance on working and short-term memory tasks and then to compare the scope of attention to primary memory. It is our belief that, like working memory, primary memory, secondary memory, and the scope of attention must change and become more efficient with increasing age. Because they are separate, but related, constructs, it seemed most likely that they would have different developmental paths in childhood, as also indicated by previous research (De Alwis et al., 2009; Foos et al., 1987) but this has not been well-established. Our second goal was to then identify if these three constructs were capable of predicting intelligence in a meaningful way. Two studies are presented that had unique influence on the current study. These two studies both focused on why working memory tasks “work” to predict intelligence and they each provided different predictions for which type of memory is important to the relationship between working memory and intelligence. They are summarized here: one representing a study that used a developmental approach incorporating the scope of attention (Cowan et al., 2005) and one representing how primary and secondary memory have been identified using working memory and short-term memory performance in adults and how primary and secondary memory each uniquely relate to intelligence (Unsworth & Engle, 2006). These articles were instrumental in the development of the methodology, as well as the hypotheses, proposed in this study.

Cowan et al. (2005) focused on how performance on typical working memory tasks (which they called storage-and-processing tasks), short-term memory tasks, and scope of attention tasks relate to one another and also to higher-order cognition abilities (like fluid intelligence and performance on standardized tests) in both children and adults. Cowan et al. felt that it was important to look at the relationship developmentally for two reasons: children often show greater variability in tasks, allowing for stronger correlation tests, and because the differences between different age groups can help us to understand the different processes and mechanisms that are functioning during any given task. With the primary question of how do working memory tasks “work” to predict higher order cognition, it is likewise important to look at differences in processes that vary across development, such as sub-vocal rehearsal or capacity differences, to understand why the relationship between working memory and fluid intelligence exists.

For example, in the second experiment of Cowan et al. (2005), participants (grades 2, 4, 6 and young adults) performed four types of tests: a short-term memory task (digit span), working memory tasks (counting and listening span tasks), scope of attention tasks (running span, auditory sequences and visual array comparison tasks) and four verbal and non-verbal intelligence/scholastic measures. Scope of attention tasks were defined as a task that required storage but the items were presented so quickly or so numerously, that it was extremely difficult for these items to be rehearsed or even placed into the phonological store by sub-vocal coding (i.e. naming all of the items to remember what was there and when/where they were presented). After all of the tasks were performed, means and age differences within tasks were calculated. Significant age differences were shown for all of the tasks with performance improving as age increased.

Then Cowan et al. (2005) analyzed the correlations between the individual tasks. All of the correlations between tasks were significant and the vast majority remained significant after age was partialled out, indicating the strong relationships between the processes involved in the short-term memory, working memory, scope of attention, and intelligence tasks. They reported the results of the regression analyses with intelligence as the criterion factor. They had hypothesized that scope of attention tasks would share a significant amount of the variance with the working memory tasks because working memory tasks include a processing element to limit rehearsal of the items to be remembered. Their prediction was supported by the result that scope of attention measures shared with working memory performance the second greatest amount of variance (13% of the total variance) that was accounted for by the model. The largest amount of variance was shared between all three of the tasks (working memory, scope of attention and short-term memory tasks).

Importantly for our purposes, they found that the short-term memory measure was a small but significant predictor of intelligence in the first regression analysis. However, when the variance associated with age was removed initially in the second regression analysis, short-term memory was no longer a significant predictor, which was interpreted to mean that digit span was a better predictor of intelligence in the younger age groups but not the older age groups. They hypothesized that this change in predictive variance was due to short-term memory being an impure measure of the scope of attention for older participants because these participants have the ability to rehearse and group items easily during the short-term memory task but cannot during the working memory and scope of attention tasks. On the other hand, the younger children do not rehearse spontaneously (Flavell, Beach, & Chinsky, 1966) so the younger participants' short-term memory performance was based on the same limited-capacity processes that their working memory performance was based upon. It was shown that a likely reason that working memory was a good predictor of intelligence was because working memory shared the same processes as scope of attention measures for all participants and the same processes that only the younger children use during short-term memory tasks. This process was hypothesized by Cowan et al. (2005) to be the scope of attention, which is the maximum capacity of the focus of attention.

In the second article that provided a key motivation for the current study, Unsworth and Engle (2006) focused on the theoretical and practical distinctions between primary and secondary memory. Their main goal was to explain why, in adults, working memory tasks correlated strongly with fluid intelligence but short-term memory tasks generally do not correlate as strongly with fluid intelligence (Daneman & Carpenter, 1980; Engle, Tuholski et al., 1999). In many experiments, short-term memory tasks start with short list-lengths and continue until the participant cannot recall the lists perfectly. In most working memory tasks, participants perform trials at short and longer list-lengths. This difference results in a difference in variability from short-term and working memory task performance which could impact the correlations with fluid intelligence. However, Unsworth and Engle believed that there was another, more theoretically important reason for the differences in relationships between short-term memory or working memory with fluid intelligence. They reasoned that because primary memory could only hold 3-4 items, short-term memory tasks with list lengths of 3 or 4 items could rely completely on primary memory capacity because all of the items could be held there. However, short-term memory tasks with long list lengths (5 or more items) measured the capacity of primary memory and the ability to retrieve from secondary memory because any items that exceeded capacity were displaced from primary memory. Working memory tasks do not measure the full capacity of primary memory because items are displaced immediately after they are put into primary memory when attention is shifted to the processing component of the task. They assumed that in a working memory task, the final item can be stored in and retrieved from primary memory because no processing component followed this final item, but this assumption was not tested until the current study. Instead, working memory tasks measure retrieval from secondary memory because the majority of the items are in secondary memory when it is time for recall. With short-term memory tasks at short list lengths, performance represented mainly primary memory capacity and only slightly the efficiency of secondary memory, but working memory task performance was heavily weighted toward the efficiency of secondary memory, leading to the differences in these tasks' performance correlating with fluid intelligence.

Using data originally gathered by Kane et al. (2004), they isolated performance on 2 different short-term memory tasks, 2 different working memory tasks, and 3 different fluid intelligence measures for 235 adults. These tasks included a word span task, a letter span task, a reading span task, an operation span task, portions of the Raven Advanced Progressive Matrices (Raven, Raven, & Court, 1998), portions of the WASI matrix reasoning (The Psychological Corporation, 1999), and portions of the BETA III test (Kellogg & Morton, 1999). The latter three of these tasks are non-verbal abstract reasoning tasks that present sample matrices of patterns with a block missing and the participant has to choose the block from a selection that would complete the matrix.

Unsworth and Engle (2006) found that there were clear differences in the probability of participants recalling items from short versus long list lengths on the short-term memory tasks. Participants had ceiling performance on list lengths of four or less, supporting their claim that these short list lengths measured the capacity of primary memory. The slope of the probabilities of recall for the longer list length conditions was more similar to the slope of probabilities in the working memory task, with performance dropping steeply as the list length increased. When comparing list lengths of 2-5 items for both the short-term and working memory tasks in a 2 x 4 ANOVA, they found that the interaction was significant and that it accounted for 69% of the variance. This significant interaction indicated a different slope across the list lengths for the two types of memory tasks. Then they compared the slope of performance for the longer list-lengths (5-7) in the short-term memory task to the working memory list lengths (2-4). This interaction was also significant, but it only accounted for 2% of the total variance, rather than 69%. This indicated that the declining slopes for working memory performance and short-term memory long-list length performance were very similar.

Next, they looked at the correlations between the different list length conditions for both types of tasks and fluid intelligence. They found that short-term memory correlations with fluid intelligence increased as list length increased but the working memory correlations with fluid intelligence were relatively constant as list length increased. Additionally, the magnitude of the correlations differed in that the working memory correlations were relatively high correlations (ranging from r = 0.35-0.45), while the short-term memory correlations only reached that level at list length 5 and above. They also found that the correlations between short-term memory and fluid intelligence and between working memory and fluid intelligence were weakened substantially when the variance associated with the other process was removed, but that the correlations between working memory performance and fluid intelligence were still significant after partialling out short-term memory performance. The longer list lengths in the short-term memory task also maintained strong correlations with fluid intelligence after the working memory performance was partialled out, perhaps indicating that the strategies used by participants in this task shared a relationship with intelligence. Also, important to note, the lower list lengths for short-term memory had very low standard deviations, indicating that there was little variability and that individuals did not differ much in primary memory capacity, which supported one of the assumptions for primary memory.

Furthermore, the authors then conducted an exploratory factor analysis to further examine how the different list lengths in working memory and short-term memory tasks were measuring separate constructs and therefore confirm the results of the regression analyses. They found three factors: 2-4 item list lengths in short-term memory, 4-7 item list lengths in short-term memory, and all the list length conditions in the working memory task. Because the 4-item list length cross-loaded onto 2 factors, they removed it from the analysis and then performed a simultaneous regression to predict fluid intelligence, followed by variance-partitioning multiple regressions to better assess which factor contributed what amount of variance. They found that the three factors predicted 28.3% of the variance and that the longer list lengths in short-term memory and working memory performance each uniquely predicted about 5% of the variance with 15% of the variance shared between these two factors. The short list length conditions in short-term memory contributed less than 1% of the variance and did not share more than 1% of the variance with the other two variables. The authors felt that the low variability present in the short list length conditions for the short-term memory task could have played a role in its lack of predictive power of fluid intelligence. To correct for this, they reanalyzed each individual participant’s primary memory capacity in accordance with the assumption that primary memory capacity is reflected by perfect recall performance (Broadbent, 1975; Cowan, 2001). They began by excluding participants with ambiguous primary memory, which they defined by looking at performance on both of the short-term memory tasks and identifying if each participant had perfect performance on each increasing list length condition until a less than perfect list length condition. This led to a primary memory capacity for each task being the greatest list length condition with perfect performance to that point. As a result of these criteria, they lost several participants with ambiguous scores. However, they found that the primary memory capacity had higher standard deviations than the short-list length conditions, which addressed the concern that the short-list length conditions had such low variability. Primary memory was smaller for word span than for letter span, but they were strongly correlated, so they averaged the two primary memory scores together to get a single primary memory score for each individual. Then they performed the correlations and regressions again with the PM memory score and found that PM was not any stronger of a predictor of fluid intelligence than the probability recall scores for the short list lengths.

Theoretical Benefits of the Current Methodology

The Unsworth and Engle (2006) approach to measuring primary memory capacity and the efficiency of secondary memory were not far removed from the former studies of these two constructs (Waugh & Norman, 1965; Watkins, 1974). They conceptualized the constructs in a similar manner, with perhaps the only exception being that they used different tasks to extract the capacity estimates than were used by previous researchers. They also focused on the theoretical limits and abilities of primary memory rather than depending on a formula to derive the capacity, like Tulving and Colotla (1968) rather than Waugh and Norman (1965). One benefit of this approach was that it allowed them to use two different tasks to get independent estimates of secondary memory and independent forgetting curves that could then be compared to one another to establish reliability. Another benefit to their approach was that they used several analytical techniques to confirm that primary memory capacity was truly distinct from secondary memory. Watkins (1974) pointed out that this was a major flaw in previous calculations of primary versus secondary memory because most methods did not take into account that the final items in the list could have been recalled from secondary memory rather than primary memory but assumed that items were recalled from secondary memory based on their placement in the list.

Considering the Cowan et al. (2005) approach to the question of why do working memory tasks “work” better than short-term memory tasks to predict intelligence also increases the possible contribution of the proposed study. Cowan et al. (2005) used similar tasks to Unsworth and Engle (2006): working memory and short-term memory tasks, with different age groups: 7-8 year-olds, 9-10 year-olds, 11-12 year-olds and young adults. Additionally, Cowan et al. performed a similar series of variance-partitioning multiple regressions as Unsworth and Engle (2006), which made their developmental study an important reference for our application of Unsworth and Engle’s (2006) methodology with children. However, the most valuable contribution of the Cowan et al. (2005) article was the theoretical differences in this model as compared to the Unsworth and Engle (2006) model. Cowan et al. (2005) had theorized that the key component shared between the three tasks (working memory, short-term memory, and scope of attention tasks) was the basic scope of attention, which is the maximum capacity of the focus of attention. The scope of attention (Cowan, 2001) is very similar theoretically to the capacity of primary memory (Unsworth & Engle, 2006). However, Unsworth and Engle showed a stronger relationship between retrieval from secondary memory and intelligence than between the capacity of primary memory and intelligence. The current study sought to examine which of the theoretical predictions would be supported.

Factors Influencing the Development of Primary and Secondary Memory

An important goal of this study was to measure the capacity of primary memory and the efficiency of secondary memory in children using similar techniques to those used by Unsworth and Engle (2006). It has been well-established that children have lower short-term and working memory spans than adults (Case et al., 1982; Cowan et al., 2005). However, the unique contribution of primary and secondary memory individually to working memory task performance had never been examined previously. There are several possible contributors to children's primary and secondary memory performance and these contributors play a role in existing working memory theories (Baddeley, 2007; Cowan, 2001). One of the main contributors to a child's primary memory capacity is the ability to rehearse items to keep them from being displaced from primary memory. Rehearsal is rarely seen in children younger than 6 or 7 years of age (Flavell, Beach, & Chinsky, 1966; Ornstein & Naus, 1978). Even when children as old as 8 years of age are instructed to use rehearsal (out loud), they often rehearse by repeating the last presented stimulus and maybe one from earlier in the list. This is contrasted with older children who tend to compile an ongoing list, constantly updating the rehearsal list with the newest item (Ornstein, Medlin, Stone, & Naus, 1985). Because of the differences in rehearsal styles, the youngest age group (8-9 year-olds) were likely less able to keep items in primary memory but the older age group (10-11 year-olds) should have been better able to use rehearsal to keep items in primary memory. An additional contributor to differences in primary memory performance could likely be simple differences in capacity. Even in tasks in which rehearsal is not possible or useful, such as scope of attention tasks, spans increase with increasing age (Cowan et al., 2005). Thus, primary memory in children was likely impacted by both rehearsal abilities and the basic capacity limits. In this way, the youngest age group's primary memory would be hindered by a smaller total capacity and by the inability to efficiently rehearse; whereas, the older age group should only differ from adults in the raw primary memory capacity.

There are also several potential contributors to a child's ability to search secondary memory. Probably the most salient contributor of secondary memory performance is the impact of proactive interference, especially when predicting fluid intelligence. It has been established that working memory tasks, such as listening span, that increase in set size length as the task continues, increases the amount of proactive interference experienced by the participant (Lustig, May, & Hasher, 2001). Bunting (2006) examined how the release and build-up of proactive interference in working memory tasks correlated with fluid intelligence performance. He had participants perform a standard working memory task where all the to-be-remembered items were words, the same working memory task but the items were either words or digits which alternated after each trial, or the same working memory task but the items switched between words and digits during each trial. He found that trials in which proactive interference had built-up were more predictive of fluid intelligence than trials in which proactive interference had been released from the change in to-be-remembered stimuli. Additionally, Lustig et al. (2001) have shown that when proactive interference is decreased in the working memory task, that the relationship between working memory performance and prose recall is decreased. Thus, previous research has clearly indicated that internal resistance to proactive interference is an important contributor to the strong relationship between secondary memory and fluid intelligence (Bunting, 2006; Lustig et al., 2001; Unsworth & Engle, 2006). Just as primary memory capacity develops with age, the ability to resist proactive interference increases with age also. Kail (2002) in a meta-analysis of the Brown-Peterson task found that children are less susceptible to proactive interference as they age from 4 years to 9 years-old (Study 1) but also from 9 years-old to young adulthood (Study 2, not a meta-analysis). Other factors that could impact efficient retrieval from secondary memory include encoding deficits and output interference, but these factors were not emphasized by Unsworth and Engle (2006, 2007a). Research on these factors in childhood is sparse but some evidence indicates that children improve in their ability to use encoding strategies and improve the amount of information that can be recalled when using these strategies (Rohwer & Bean, 1973; Shing, Werkle-Bergner, Li, & Lindenberger, 2008). The three age groups, 8-9 year-olds, 10-11 year-olds and young adults, were selected for the current study because of the theoretical differences between the groups in terms of rehearsal processes and vulnerability to interference as well as overall brain development.

Summary

In summary, the current study sought to measure primary memory, secondary memory, and the scope of attention in two age groups of children and a group of young adults and then to identify how those three capacities related to fluid intelligence. Additionally, this research was conducted with the goal of further explanation of why Cowan et al. (2005) found that children's short-term memory performance was a good predictor of intelligence when previous studies using similar methods in adults (Engle, Tuholski et al., 1999) have failed to find the relationship between short-term memory and intelligence. We selected two different age groups of children for multiple reasons. Both child groups were likely to have greater variance in performance than the adult group allowing for greater opportunity to examine the relationship between primary memory and fluid intelligence. The 8-9 year-old group was specifically chosen because they are not likely to use rehearsal strategies and have poorer control of inhibition important to secondary memory. Finally, the 10-11 year-old group was chosen because they are likely to use rehearsal well and have better control over interference, but still do not have completed brain development compared with the young adults.

METHOD

Participants

Participants from three age groups completed the study. The youngest age group was 8-9 years-old and they were enrolled in the third grade at the time of the study. There were 36 children (*M* age = 107 months, *SD* = 6.75, 15 males) from this age group that were included in the final sample. Four children participated but were not included in the final sample: 3 children did not complete all of the tasks either due to scheduling conflicts or technical difficulties and 1 child reported speaking a first language that was not English. The middle age group was 10-11 years-old and they were enrolled in the fifth grade at the time of the study. There were 34 children (*M* age = 134.56 months, *SD* = 5.8, 16 males) that were included in the final sample. Two children in this age group were not included in the final sample because they did not complete all parts of the study due to scheduling issues. The child participants were recruited from several schools in the Baton Rouge area, as well as from connections with psychology undergraduate students at LSU and the researchers. They received two small toys and an honorary junior scientist certificate as compensation for their participation. The oldest age group was enrolled in psychology courses as undergraduate students at Louisiana State University. There were 53 participants in this group that were included in the final sample (*M* age = 20.19 years, range = 18-34, *SD* = 2.68, 9 males). In this group, 11 adults participated but were not included in the final sample: 1 was excluded because of reported hearing loss, 3 were excluded because they reported taking a medication that affects cognitive processes, 3 were excluded because they reported speaking a first language that was not English, and 4 were excluded because there were technical problems with one or more of the tasks and they were not completed. Adult participants were compensated with course credit in psychology courses at Louisiana State University.

Materials

The materials for this experiment consisted of 6 computerized programs and 3 pencil-and-paper fluid intelligence measures. The two short-term memory programs included a digit span and a word span task. Each of these tasks presented their items (digits or words) at a rate of 1 per second and included set sizes from 1 item to 7 items, which were presented randomly to reduce excessive build-up of proactive interference and to replicate the method of Unsworth and Engle (2006). Four trials at each set size condition were presented. The digits included 1-9 and the words were one-two syllable concrete words of high frequency of usage in the language (See Appendix A). No items were repeated within a trial. The tasks started with three practice trials (one 2-item and two 3-item set size trials, respectively) that were not included in the final analysis.

The two working memory programs included a counting span and a listening span task. Each of the trials in these tasks started with a processing portion (either the participant counted the number of target items or listened to a sentence and determined if it was true) and then required the participant to remember the result of the process (the total number of items or the last word in the sentence) until the recall phase at the end of the trial. There were between 1 and 5 processing components, and therefore, also 1-5 items to remember, in each trial and the order was randomly presented to reduce proactive interference and replicate Unsworth and Engle (2006). Participants received 3 practice trials at the beginning of the task (one 1-item and two 2-item set size trials). In each task, there were 4 trials at each list length for a total of 20 scored trials. When performing the counting span, participants were asked to number out-loud the blue squares on the screen, while ignoring the red triangles, as quickly as possible. The screen had between 2 and 9 squares and between 2 and 9 triangles, which was randomly determined, with the qualification that no screen had fewer than 5 items or more than 15 (See Appendix B for the screen shots of the pictures; Towse & Hitch, 1995). When performing the listening span, participants heard a short sentence, determined and stated whether it was true or false, and then repeated the last word of the sentence which was the to-be-recalled information at the end of the trial (See Appendix C for the sentences used, as well as the overall accuracy of determining if it made sense for each sentence). This task was modeled from a listening span task used by Cowan et al. (2003), which was modeled after Kail and Hall (1999) and Daneman and Carpenter (1982). Set size 1 was included in both the short-term and working memory tasks for two purposes: to ensure that we could accurately measure primary memory in children, and also to test Unsworth and Engle's (2006) assumption that 1 item is held in primary memory during working memory tasks.

The two scope of attention measures that were utilized included a running span task and a visual array comparison task (both used previously by Cowan et al., 2005). During the running span task, participants heard digits spoken at a rate of 4 per second and after a variable number of digits (between 12 and 20, only the even values) and after the digits stopped, the participant was required to recall as many of the final digits as possible (up to 10 digits) that were presented in serial order (Pollack, Johnson, & Knaff, 1959). If the participant knew that there was a digit presented in a certain position but could not remember what it was, then a placeholder "m" was used in that position. This task was scored by taking the mean number of items correctly recalled in the correct serial position across all of the list lengths. In the visual array comparison task, participants viewed a briefly displayed (250 ms) array of various colored squares, followed by a mask screen, and then the test array (adapted from Luck & Vogel, 1997). In the test array, the same squares as in the study array were displayed with one possible exception: the test item. The test item was a circled square in the same location as a square from the study array but it was either the same color as in the study array or a different color. The participant was asked to determine if the square was the same color (by pressing the s key) or a different color (by pressing the d key) when compared to the study array. Each array contained 4, 6, 8, or 10 squares and there were 8 practice trials and 36 scored trials, with an equal number of trials with each different array amount. This task was scored with a formula originally designed by Pashler (1988) but modified by Cowan (2001) to provide a closer estimate of the capacity of the scope of attention. This formula is $k = N * (H + \mathrm{CR} - 1)/\mathrm{CR}$, where k represents the items that receive attention from the array, N represents the number of items in the array, H represents the observed rate of accuracy when the target item color is the same, and CR represents the correct rejections when the target item color is different.

Three measures of general fluid intelligence were collected in addition to the other measures. These three measures included the Raven's Standard Progressive Matrices, the Wechsler's Intelligence Scale for Children (WISC-IV; The Psychological Corporation, 2003) block design subtest, and the WISC-IV matrix reasoning subtest. The Raven's Matrices displayed a black and white pattern and offered 6-8 options that could complete the pattern. There were sixty problems total, split into 5 different subtests, each increased in difficulty. In the WISC-IV block design subtest, participants were shown a design of a combination of smaller blocks and then were asked to copy the design with their set of blocks. In the WISC-IV matrix reasoning subtest, participants were shown a series of color pictures and then asked to complete the series by selecting the correct one from five options. The WISC assessments are one of the top two intelligence tests used for placement of children into different learning environments (Flanagan & Kaufman, 2004).

Procedure

Participants performed the nine tasks in either one single session (with a long break halfway through the tasks) or two separate sessions. The tasks were divided with the memory tasks during the first session and intelligence tasks and scope of attention tasks during the second session. The task order was constant across all participants: digit span, counting span, word span, listening span during the first session, and WISC matrix reasoning, visual array comparison task, WISC block design, running span, and finally Raven's Matrices during the second session (fixed order of tasks was also used by Cowan et al., 2005 and is standard practice in individual differences research).

The entire young adult group completed all of the tasks in a single session, with a 10-15 minute break, lasting about 2 hours total. The child groups either completed the tasks in a single session lasting about 3 hours, with a 30 minute-one hour break halfway through or in two sessions each lasting between 45 minutes and 1 hour. In the 8-9 year-old group, 12 participants completed the study in a single session and 24 participants completed the study in two sessions. For those that completed the tasks in a single session, the mean break was 47.67 minutes long (*SD* = 14.56, range 34-77 min.). For those that completed the tasks in two sessions, the mean number of days between the first and second session was 5.25 days (*SD* = 6.94, range 1-33 days). Only three of these participants had more than 7 days between their first and second sessions.

In the 10-11 year-old group, 21 participants completed the study in a single session and 13 completed the study in two sessions. For those that completed the tasks in a single session, the mean break was 49.05 minutes long (*SD* = 14.82, range 15-69 min.). For those that completed the tasks in two sessions, the mean number of days between the first and second session was 5.84 days (*SD* = 5.11, range 1-19 days). Only three of these participants had more than 7 days between their first and second sessions.

All tasks were individually administered and the experimenter entered all verbal responses from the short-term and working memory tasks from the child participants. The adult participants were allowed to input their own responses during the digit and word span tasks but not the counting or listening span tasks. All of the participants were allowed to enter their own responses for the scope of attention tasks.

RESULTS

Several different types of analyses were conducted with the resulting data. There were five primary variables of interest: age group, short-term memory task performance, working memory task performance, scope of attention task performance, and fluid intelligence task performance. There were many goals of the analyses of these variables. One goal was to better understand developmental differences in primary memory capacity, secondary memory retrieval ability, and the capacity of the scope of attention so these three factors were calculated for each of the age groups. We also wanted to demonstrate that different parts of short-term memory tasks were drawn primarily from primary memory but other parts of the short-term memory task and most of the working memory task measures secondary memory retrieval, as was demonstrated by Unsworth and Engle (2006). This goal included a desire to compare performance on the tasks between the three age groups, as further evidence of the developmental differences between primary and secondary memory. Finally, we also sought to examine the potentially different relationships between short-term memory performance, working memory performance, scope of attention task performance, and fluid intelligence within each age group and across all age groups. The analyses designed to meet this goal were intended to allow a test of the Unsworth and Engle (2006) model of secondary memory predicting fluid intelligence and the Cowan et al. (2005) model of the scope of attention (which was theoretically very similar to primary memory) predicting fluid intelligence, as well as the short-term memory task performance in the child age groups.

Within each section, each age group was described starting with the young adult age group and then followed by the 8-9 year-old age group and finally the 10-11 year-old age group. We began with descriptive statistics for the variables of interest and examined the Pearson *r* correlations between these variables of interest. We followed this with an analysis of the parts of the short-term memory and working memory tasks to assess which aspects of these tasks measure primary and secondary memory. This analysis was conducted with all groups combined, followed by each age group separately to assess the developmental differences in each task's performance. The next set of analyses was designed to measure the strengths of the relationships between the parts of the tasks measuring secondary memory and fluid intelligence and then contrasted those relationships with the much poorer correlations between the parts of the tasks meant to measure primary memory capacity. We then measured the age differences in the scope of attention and the relationship between the scope of attention and fluid intelligence. Finally, the last set of analyses utilized the four predictor variables (age, primary memory, secondary memory, and the scope of attention) and the ability of these variables to predict fluid intelligence performance, using multiple regression analyses and variance partitioning regression techniques.

Descriptive Statistics

As stated earlier, there were five primary variables of interest: age group, short-term memory task performance, working memory task performance, scope of attention task performance, and fluid intelligence task performance. Composite measures were used for all of these variables except age group. For the two main memory variables: the list lengths in the short-term memory tasks, and the list lengths in the working memory tasks, a composite score was created by averaging the proportion correct at each list length. For instance, an individual's proportion correct score for list length 3 for the digit span was averaged with that individual's proportion correct score for the list length 3 for the word span to represent the list length 3 proportion correct of the short-term memory tasks. For the scope of attention performance, we took the average number of items recalled accurately across the different list lengths in the auditory running span and averaged that number with the Cowan's *k* score for the visual array comparison performance. The *k* score represents the capacity of the scope of attention taking into account the possibility of guessing. The fluid intelligence task composite score was an average of the *z* scores for the three tasks. Tables 1 through 3 show the means and standard deviations of the composite scores, as well as the Pearson *r* correlations for each age group separately. See Appendix D for the means and correlations for each of the different tasks and the different measurement techniques. See Appendix E for reliability scores calculated with Cronbach's α for the memory and scope of attention tasks, as well as reported reliability scores for the fluid intelligence tasks.

Table 1. Means, Standard deviations, and Correlations for the composite list length conditions, composite scope of attention, and composite fluid intelligence for the adult group

	Mean	*SD*	1	2	3	4	5	6	7	8	9	10	11	12	13
1. STM LL1	1.00	.02	--												
2. STM LL2	1.00	.00	-	--											
3. STM LL3	1.00	.01	-0.04	-	--										
4. STM LL4	.99	.03	0.36**	-	-0.11	--									
5. STM LL5	.92	.06	0.18	-	0.04	0.38**	--								
6. STM LL6	.79	.14	0.32*	-	-0.12	0.31*	0.55**	--							
7. STM LL7	.67	.16	0.24	-	-0.09	0.32*	0.59**	0.69**	--						
8. WM LL1	.99	.04	-0.05	-	0.23	-0.14	-0.20	-0.20	-0.07	--					
9. WM LL2	.97	.08	-0.39**	-	-0.08	0.12	0.02	0.13	0.00	0.06	--				
10. WM LL3	.88	.15	0.12	-	-0.08	0.44**	0.16	0.29*	0.27	-0.06	0.38**	--			
11. WM LL4	.72	.17	0.32*	-	-0.27^	0.42**	0.27*	0.35*	0.39**	-0.24	0.38**	0.62**	--		
12. WM LL5	.53	.20	0.29*	-	-0.26	0.41**	0.43**	0.32*	0.39**	-0.24	0.37**	0.65**	0.66**	--	
13. gF	.00	.84	0.13	-	-0.09	0.27*	0.16	0.16	0.16	-0.18	0.06	0.34*	0.21	0.48*	--
14. Scope	3.77	.57	0.05	-	-0.10	0.22	0.43**	0.33*	0.46**	-0.24	0.11	0.27*	0.23	0.42**	0.41**

Note: * indicates $p < 0.05$; ** indicates $p < 0.01$; LL stands for list length; STM stands for short-term memory; WM stands for working memory; gF stands for fluid intelligence. The short-term memory list length condition 2 had no variance so it could not be correlated.

In examining Tables 1-3, it became evident that the 10-11 year-old group was different from the other two age groups in the total number of significant correlations, especially in the lack of correlations between the list length conditions and the fluid intelligence measure. To examine the difference between this age group and the other two age groups, we started by looking at the correlations between the tasks. We found that the three fluid intelligence scores were not strongly correlated. Only one of the three correlations was significant. This lack of similarity between the tasks selected to measure the same construct was only present in this age group and was likely behind the lack of significant relationships between fluid intelligence and the other important factors in the current study. We also examined the scatterplots between

Table 2. Means, Standard deviations, and Correlations for the composite list length conditions, composite scope of attention, and composite fluid intelligence for the 8-9 year-old group

	Mean	*SD*	1	2	3	4	5	6	7	8	9	10	11	12	13
1. STM LL1	.99	.03													
2. STM LL2	.99	.04	0.32												
3. STM LL3	.95	.08	-0.02	0.02											
4. STM LL4	.79	.17	0.23	0.16	0.44**										
5. STM LL5	.59	.20	0.05	0.13	0.43**	0.66**									
6. STM LL6	.41	.18	0.14	0.03	0.47**	0.58**	0.73**								
7. STM LL7	.30	.15	0.17	0.11	0.38*	0.47**	0.68**	0.76**							
8. WM LL1	.97	.07	-0.11	-0.17	0.77**	0.15	0.26	0.41*	0.36*						
9. WM LL2	.85	.15	-0.09	0.27	0.51**	0.28	0.36*	0.31	0.32	0.34*					
10. WM LL3	.58	.17	0.11	0.29	0.50**	0.53**	0.69**	0.52**	0.34*	0.29	0.38*				
11. WM LL4	.39	.17	-0.01	0.32	0.37*	0.26	0.42*	0.40*	0.41*	0.30	0.58**	0.52**			
12. WM LL5	.26	.15	0.12	0.17	0.48**	0.54**	0.55**	0.48**	0.19	0.29	0.40*	0.69**	0.57**		
13. gF	.00	.87	0.09	0.05	0.49**	0.35*	0.44**	0.56**	0.55**	0.52**	0.44**	0.41*	0.38*	0.31	
14. Scope	2.57	.76	0.13	0.24	0.22	0.42*	0.26	0.21	0.09	0.15	0.29	0.27	0.36*	0.44**	0.35*

Note: * indicates $p < 0.05$; ** indicates $p < 0.01$; LL stands for list length; STM stands for short-term memory; WM stands for working memory; gF stands for fluid intelligence.

Table 3. Means, Standard deviations, and Correlations for the composite list length conditions, composite scope of attention, and composite fluid intelligence for the 10-11 year-old group

	Mean	*SD*	1	2	3	4	5	6	7	8	9	10	11	12	13
1. STM LL1	1.00	.02													
2. STM LL2	.99	.02	-0.08												
3. STM LL3	.98	.04	0.27	-0.18											
4. STM LL4	.88	.09	0.33	0.04	0.24										
5. STM LL5	.63	.14	0.16	0.24	0.06	0.32									
6. STM LL6	.48	.15	0.36*	-0.04	0.34	0.25	0.56**								
7. STM LL7	.37	.13	0.30	0.00	0.15	0.17	0.51**	0.65**							
8. WM LL1	.98	.06	0.70**	-0.01	0.06	0.42*	0.16	0.27	0.15						
9. WM LL2	.91	.10	-0.16	0.43*	-0.12	0.05	0.35*	0.08	-0.03	0.21					
10. WM LL3	.76	.15	0.26	0.28	0.34*	0.17	0.36*	0.40*	0.31	0.34*	0.48**				
11. WM LL4	.54	.14	0.01	0.37*	0.12	-0.12	0.13	0.28	0.25	-0.08	0.32	0.29			
12. WM LL5	.37	.13	0.10	0.17	0.42*	0.05	0.11	-0.06	0.14	-0.08	0.05	0.33	0.35*		
13. gF	.00	.71	0.25	-0.05	0.17	0.13	-0.03	-0.14	0.04	0.05	-0.25	-0.10	-0.16	0.35*	
14. Scope	2.86	.69	0.03	-0.01	0.01	0.23	0.38*	0.08	0.12	0.20	0.27	0.25	-0.01	-0.12	0.16

Note: * indicates $p < 0.05$; ** indicates $p < 0.01$; LL stands for list length; STM stands for short-term memory; WM stands for working memory; gF stands for fluid intelligence.

working memory cumulative span and fluid intelligence and between short-term memory cumulative span and fluid intelligence. These scatterplots demonstrated an overall lack of relationship between the three factors for this age group. Two participants met a definition of an outlier by having scores beyond 2.5 standard deviations of the mean for the working memory cumulative span and for one of the fluid intelligence measures. There were not any participants that had extreme scores for the short-term memory span. After removing these two participants, the correlations were calculated again and there was no improvement in the magnitude of the correlations so the participants were reincorporated with the rest of the sample. This age group seemed to lack the consistency of scores in the other two age groups.

Table 4 shows the average primary memory and secondary estimates for each age group, as well as the average short-term memory span and working memory span scores. This table was intended to test the assertions by Unsworth and Engle (2006) that the capacity of primary memory combined with the retrieval ability of secondary memory can be used to create what has typically been referred to as short-term memory span and working memory span. The average primary memory capacity estimate was calculated with each of the short-term memory tasks by looking for the highest list length condition with perfect performance and only perfect performance before the list length. Then the primary memory capacity was the average of the highest perfect list length condition from each of the short-term memory tasks (see Appendix D for the span scores for each task). The secondary memory estimate was also taken from the short-term memory tasks and was the difference between an individual’s primary memory capacity and his/her traditional span score (see below) for each task. An average was taken of the secondary memory estimate from each short-term memory task as well. The short-term memory and working memory span capacities were calculated in the same manner. The calculation was determined by examining performance across all of the list length conditions and finding the highest list length condition in which two of the four trials were correct. Then an average of the two tasks was calculated and can be seen in Table 4.

The young adult group's short-term memory span and working memory span were a little below average for these tasks compared to the reported means from Cowan et al. (2005). The short-term memory spans for the 8-9 year-old group and the 10-11 year-old group was also lower than the digit span means reported in Cowan et al. (2005). This difference was likely due to the combination of word span and digit span, with word span having a smaller span than digit span. The difference between the age groups was larger for primary memory capacity than for secondary memory retrieval.

Table 4. The Average Primary Memory (PM), Secondary Memory (SM), Short-term Memory (STM) and Working Memory (WM) Capacities for each age group

	PM	SM	STM Span	WM Span
8-9 yr olds	2.90	1.99	4.17	2.68
10-11 yr olds	2.97	2.15	4.53	3.12
Adults	4.43	1.98	6.05	3.89

Probability of Correct Serial Recall

To preliminarily examine the assumptions of primary and secondary memory with the current data set in terms of the items correct per list length, we began by examining the proportion of items recalled in the correct serial position for each of the list length conditions with all of the three age groups. We compared the age group, list length condition and task differences by using a 3 (age group: 8-9 year-olds, 10-11 year-olds, and young adults) x 2 (short-term memory and working memory) x 4 (list lengths 2, 3, 4, and 5) mixed factorial ANOVA, with a Greenhouse-Geisser correction when necessary for the violation of sphericity. There was a significant main effect of age group, F (2, 120) = 76.09, $p < 0.01$, partial $\eta^2 = 0.56$. The young adult group had the highest recall proportion ($M = 0.88$, $SE = 0.01$) followed by the 10-11 year-old group ($M = 0.76$, $SE = 0.01$) followed by the 8-9 year-old group with the lowest recall ($M = 0.67$, $SE = 0.01$). Each of the age groups was significantly different from the other two. There was a significant main effect of task, F (1, 120) = 684.48, $p < 0.01$, partial $\eta^2 = 0.85$. Recall performance was significantly higher in the short-term memory task ($M = 0.89$, $SE = 0.01$) than in the working memory task ($M = 0.65$, $SE = 0.01$). There was a significant main effect of list length, F (2.62, 314.79) = 795.32, $p < 0.01$, partial $\eta^2 = 0.87$. Each of the list lengths was significantly different than the others. The lowest list lengths had the highest recall levels and recall performance dropped as the list length increased (list lengths 2, 3, 4, and 5 respectively: Ms = 0.95, 0.86, 0.72, and 0.55; SEs = 0.01, 0.01, 0.01, and 0.01). These main effects were qualified by three significant 2-way interactions: age and task, F (2, 120) = 12.20, $p < 0.01$, partial $\eta^2 = 0.17$; age and list length, F (5.25, 314.79) = 33.15, $p < 0.01$, partial $\eta^2 = 0.36$; task and list length, F (2.80, 334.65) = 88.21, $p < 0.01$, partial $\eta^2 = 0.42$. These significant interactions were also qualified by a significant three way interaction of age, task, and list length, F (5.59, 335.64) = 12.00, $p < 0.01$, partial $\eta^2 = 0.17$. See Figure 1 for the means for each of these conditions. The three-way interaction appeared to be driven by the different rates of decreasing performance, with the short-term memory tasks showing a less drastic rate of decrease than the working memory tasks and the younger age groups showing a more dramatic decrease in performance across the list length conditions than the adult group. This analysis was followed by analyses for each age group separately to better identify the relationship between the type of task and the list length conditions.

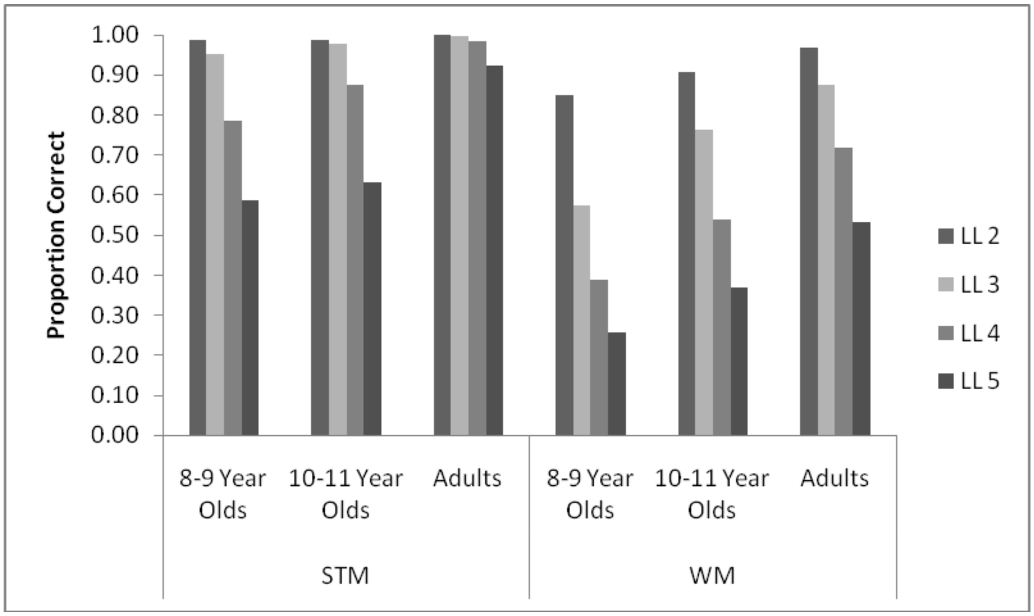

Figure 1. The accuracy in proportion-correct for each list length condition in working memory and short-term memory tasks for each of the three age groups.

For the young adults, we compared the list length conditions and the task differences by using a 2 (short-term memory and working memory) x 4 (list lengths 2, 3, 4 and 5) repeated-measures Analysis of Variance (ANOVA), with a Greenhouse-Geisser correction when necessary for the violation of sphericity. There was a significant main effect of task, with a higher proportion of items recalled in the short-term memory tasks (*M* = 0.98, *SE* = 0.00) than in the working memory tasks (*M* = 0.77, *SE* = 0.02), *F* (1, 52) = 160.84, $p < 0.01$, partial $\eta^2 = 0.76$. There was also a significant main effect of the list length condition: 2, 3, 4, and 5 (*M*s = 0.98, 0.94, 0.85, and 0.73; *SE*s = 0.01, 0.01, 0.01, and 0.02), *F* (2.43, 126.44) = 172.97, $p < 0.01$, partial $\eta^2 = 0.77$. All of the list length conditions were significantly different, with the proportion correct decreasing as the list length increased. Finally, there was a significant interaction between the type and list length, *F* (3, 156) = 121.88, $p < 0.01$, partial $\eta^2 = 0.70$. This interaction can be seen in Figure 2. The slope of the working memory task performance was steeper for the list lengths tested than the slope of the short-term memory task. These findings closely replicated the findings of Unsworth and Engle (2006).

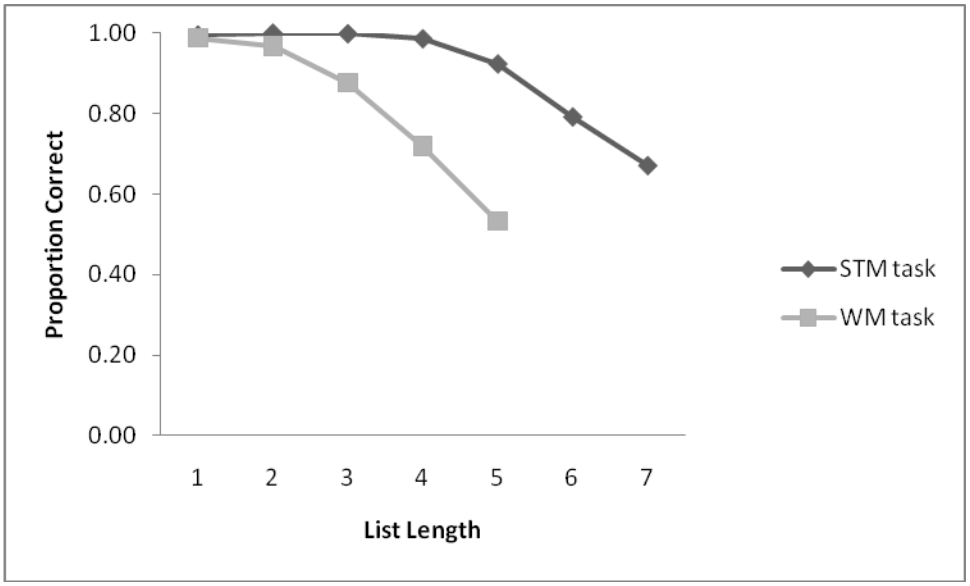

Figure 2. The accuracy in proportion-correct for each list length condition in working memory and short-term memory tasks for the adult group

This ANOVA was followed by a 2 x 3 repeated-measures ANOVA to examine if the slopes of certain list length conditions are more similar due to these list lengths predicted relationship to secondary memory measurement. The three list lengths compared were the list length 5, 6, and 7 in the short-term memory tasks and list lengths 3, 4, and 5 in the working memory tasks. There was once again a significant main effect of task with a higher proportion of items correctly recalled in the short-term memory tasks ($M = 0.80$, $SE = 0.02$) than the working memory tasks ($M = 0.71$, $SE = 0.02$), $F\ (1, 52) = 19.77$, $p < 0.01$, partial $\eta^2 = 0.28$. There was also a significant main effect of the list length condition with the shorter list lengths having higher proportions of items recalled correctly, $F\ (2, 104) = 233.41$, $p < 0.01$, partial $\eta^2 = 0.82$. Most importantly, there was a significant interaction between task and list length, $F\ (2, 104) = 6.88$, $p < 0.01$, partial $\eta^2 = 0.12$. This interaction is important, not because it was significant, but because the amount of variance accounted for by this interaction was only 12% but it was 70% in the previously reported ANOVA. This decrease in the partial η^2 indicates that the difference between the slopes is much smaller when the list lengths believed to measure secondary memory are compared than when the slopes including primary and secondary memory are compared. The similarity between the slopes can be seen in Figure 3. These results closely replicated the findings of Unsworth and Engle (2006).

Similar ANOVAs were computed for the data from the 8-9 year-olds. A 2 (task) x 4 (list length: 2, 3, 4, and 5) repeated-measures ANOVA found a significant main effect of task, *F* (1, 35) = 397.80, $p < 0.01$, partial $\eta^2 = 0.92$. This result indicated that memory performance was better for the short-term memory tasks (*M* = .83, *SE* = .02) than for the working memory tasks (*M* = .52, *SE* = .02). There was also a main effect of the list length condition with poorer memory performance in the longer list length conditions, all being significantly different than each other, *F* (2.43, 85.18) = 281.56, $p < 0.01$, partial $\eta^2 = 0.89$. The means and standard errors for the list length conditions were as follows: list length 2 *M* = 0.92, *SE* = 0.01, list length 3 *M* = 0.76, *SE* = .02, list length 4 *M* = 0.59, *SE* = 0.02, list length 5 *M* = 0.42, *SE* = 0.03. Finally, there was a significant interaction of task and list length, *F* (3, 105) = 18.65, $p < 0.01$, partial $\eta^2 = 0.35$. Figure 4 shows the proportions of each list length recalled correctly for each of the tasks.

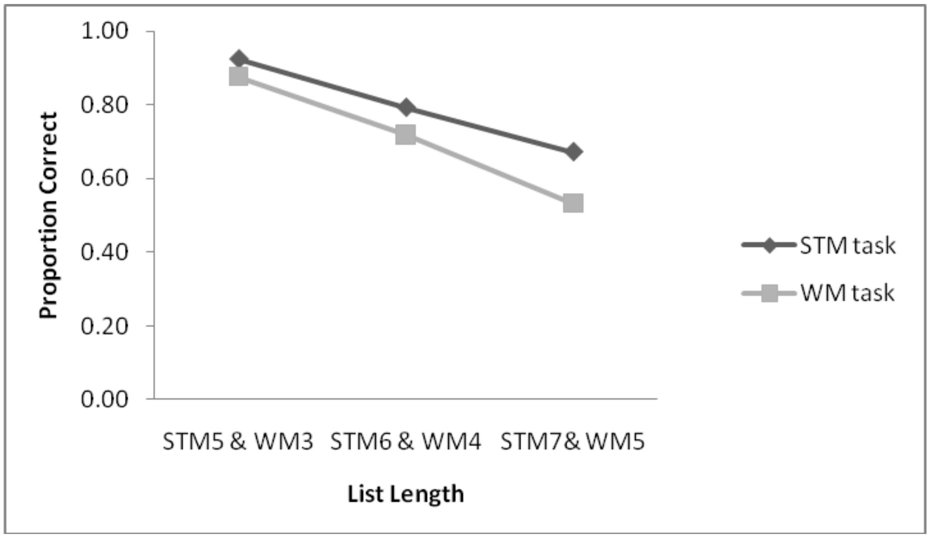

Figure 3. The accuracy in proportion-correct for the long list lengths in the working memory and short-term memory tasks for the adult group

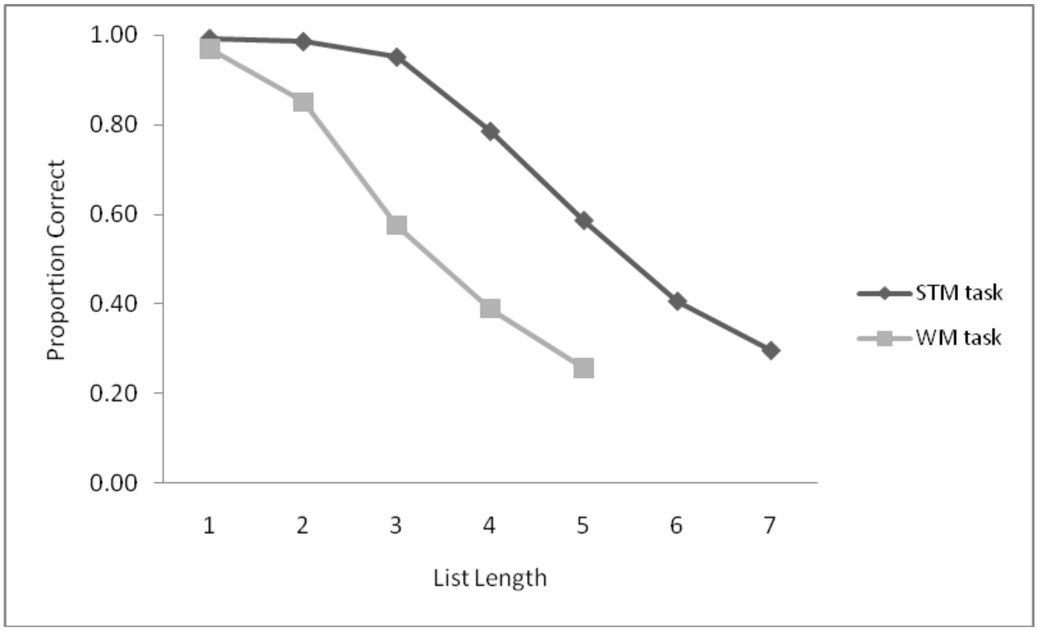

Figure 4. The accuracy in proportion-correct for each list length condition in working memory and short-term memory tasks for the 8-9 year-old group

Then, the 2 (task) x 3 (list lengths: short-term memory 5, 6, and 7 and working memory 3, 4, and 5) ANOVA was computed. There was not a significant main effect of task (short-term memory $M = .43$, $SE = .026$, working memory $M = .41$, $SE = .023$), $F\ (1, 35) = .97$, $p = .33$, partial $\eta^2 = 0.03$. There was a significant main effect of list length, $F\ (1.63, 56.90) = 163.44$, $p < 0.01$, partial $\eta^2 = 0.82$. Importantly, there was not a significant interaction between task and list length, $F\ (2, 70) = .38$, $p = 0.69$, partial $\eta^2 = 0.01$. This finding differs from the young adult group, in which the interaction was still significant but accounted for much less variance when the longer list lengths were compared. In contrast, in the 8-9 year-old group, the interaction was no longer significant when the longer list lengths in each task were compared. Figure 5 shows the slopes of the list lengths for the different tasks.

For the 10-11 year-old group, the same ANOVAs were computed. A 2 (task) x 4 (list length: 2, 3, 4, and 5) repeated-measures ANOVA found a significant main effect of task, $F\ (1, 33) = 233.76$, $p < 0.01$, partial $\eta^2 = 0.88$. This result indicated that memory performance was better for the short-term memory tasks (*M* = 0.87, *SE* = 0.01) than for the working memory tasks (*M* = 0.65, *SE* = 0.02). There was also a main effect of the list length condition with poorer memory performance in the longer list length conditions, all being significantly different than each other, *F* (3, 99) = 325.46, $p < 0.01$, partial $\eta^2 = 0.91$. The means and standard errors for the list length conditions were as follows: list length 2 *M* = 0.95, *SE* = 0.01, list length 3 *M* = 0.87, *SE* = 0.02, list length 4 *M* = 0.71, *SE* = 0.01, list length 5 *M* = 0.50, *SE* = 0.02. Finally, there was a significant interaction of task and list length, *F* (2.34, 77.08) = 19.38, $p < 0.01$, partial η^2 = 0.37. Figure 6 shows the proportions of each list length recalled correctly for each of the tasks.

Then, the 2 (task) x 3 (list lengths: short-term memory 5, 6, and 7 and working memory 3, 4, and 5) ANOVA was computed. There was a significant main effect of task (short-term memory *M* = 0.50, *SE* = 0.02, working memory *M* = 0.56, *SE* = 0.02), *F* (1, 33) = 7.90, $p < 0.01$, partial $\eta^2 = 0.19$. There was a significant main effect of list length, *F* (2, 66) = 149.05, $p < 0.01$, partial $\eta^2 = 0.82$. Importantly, there was a significant interaction between task and list length, *F* (2, 66) = 8.35, $p < 0.01$, partial $\eta^2 = 0.20$. The 10-11 year-old group was more similar to the young adult group; the interaction was significant when the longer list lengths were compared but the interaction accounted for less variance in this comparison than when the same list lengths were compared. Figure 7 shows the proportions of each list length recalled correctly for each of the tasks for the longer list length conditions.

Correlations Between Proportion-Correct for List Length Condition and Fluid Intelligence

The next series of analyses examined how the proportion of correct recall for each list length condition was related to fluid intelligence. The main purpose was to determine if the longer list lengths in the short-term memory task would correlate more strongly with fluid

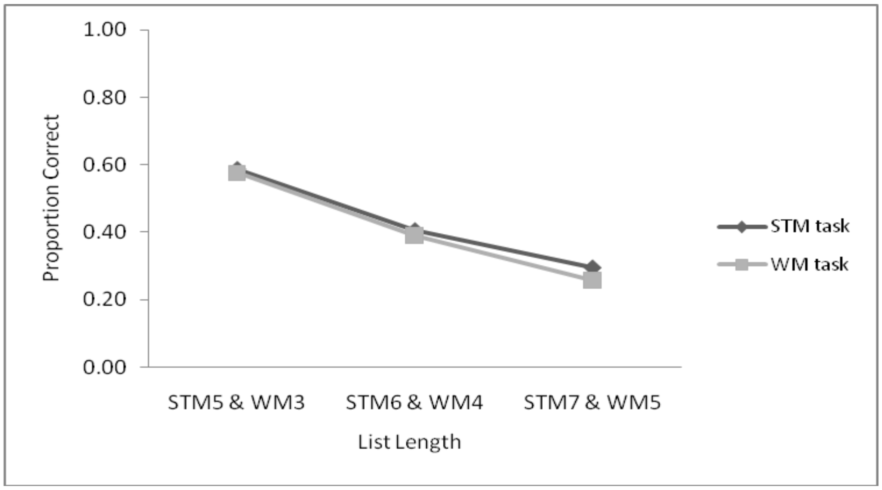

Figure 5. The accuracy in proportion-correct for the long list lengths in the working memory and short-term memory tasks for the 8-9 year-old group

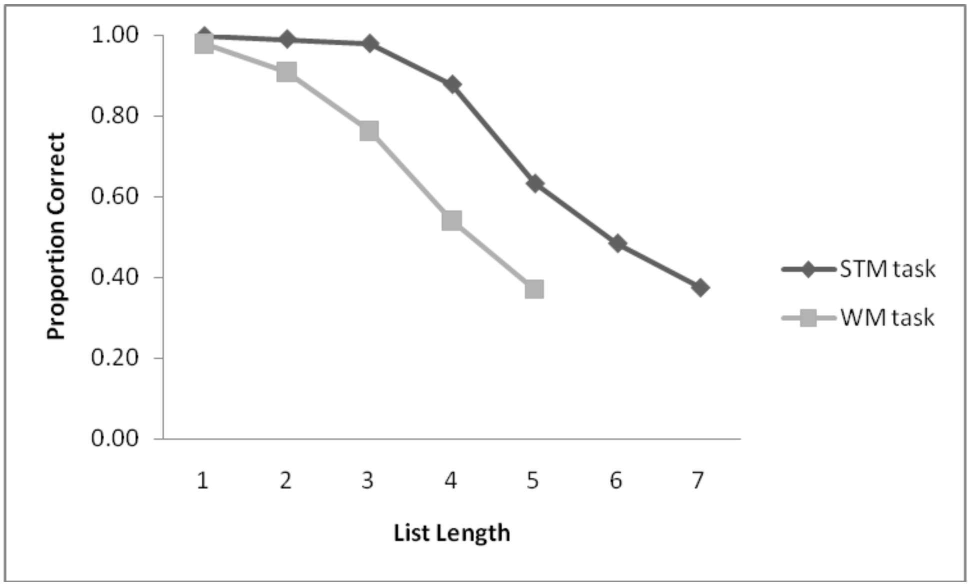

Figure 6. The accuracy in proportion-correct for each list length condition in working memory and short-term memory tasks for the 10-11 year-old group

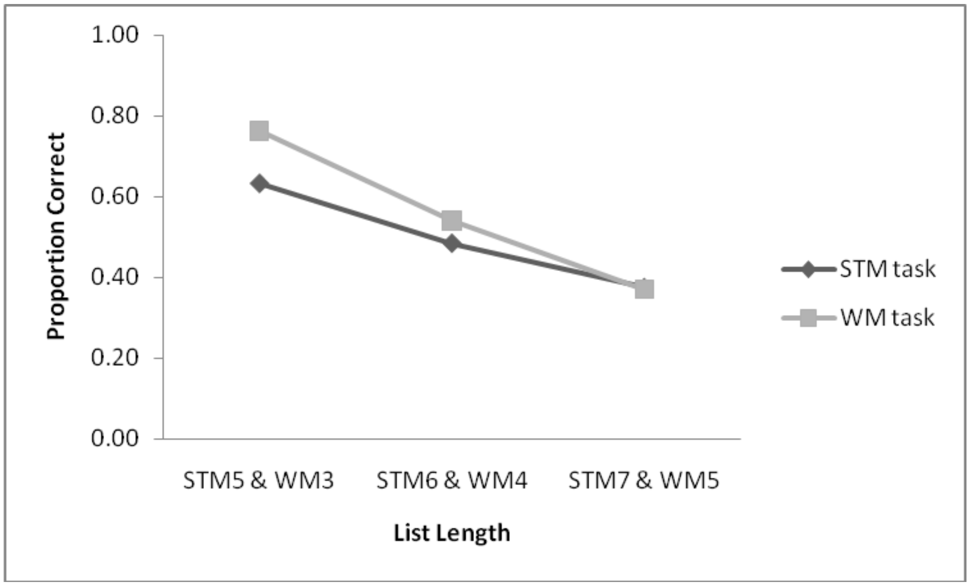

Figure 7. The accuracy in proportion-correct for the long list lengths in the working memory and short-term memory tasks for the 10-11 year-old group

intelligence than the shorter list lengths. The longer list lengths should have a stronger relationship with intelligence according to Unsworth and Engle (2006) because these list length conditions measure the influence of retrieval from secondary memory, whereas, the shorter list length conditions can be completely recalled from primary memory capacity. After calculating the raw correlations, we then calculated the partial correlations between the short-term memory list lengths and intelligence without the influence of the working memory list lengths. The working memory list lengths 2-5 were also hypothesized to draw on secondary memory retrieval, thus by partialling out the variance associated with these list lengths from the short-term memory list lengths, we should show that the partial correlations for the longer list lengths decreased substantially. Figures 8 (short-term memory) and 9 (working memory) show the results for the young adults, Figures 10 and 11 show the results for the 8-9 year-olds and Figures 12 and 13 show the results for the 10-11 year-olds.

For the young adults in the short-term memory tasks, only the list length 4 correlation with intelligence was significant before working memory list lengths (1-5) were partialled out and none of the correlations were significant after they were partialled out. For the young adults in the working memory tasks, the list lengths 3 and 5 were significant before the short-term list lengths (1, 3-7) were partialled out, and list length 5 remained significant after the short-term list lengths were partialled out. All of the conditions have much smaller correlations. This pattern of correlations only partially replicated the findings of Unsworth and Engle (2006). They found that the all of the longer list lengths (5-7) in the short-term memory tasks correlated with fluid intelligence until they partialled out the working memory tasks conditions, and the resulting correlations were still significant but much smaller than before. However, the working memory conditions were all significantly correlated with intelligence before partialling out the short-term memory tasks conditions, and the correlations were much smaller after partialling out the short-term memory task conditions.

For the 8-9 year-old group, the correlations were much stronger than in the young adult group. The short-term memory tasks list lengths 3-7 were significantly correlated with intelligence before the working memory tasks conditions were partialled out. After the working memory conditions were partialled out, the correlations all decreased in magnitude, with only list lengths 6 and 7 remaining significantly correlated with intelligence. For the working memory tasks, list lengths 1-4 were all significantly correlated with intelligence and after the short-term memory performance was partialled out, none of the correlations were significant. The 8-9 year-old age group matched the results found by Unsworth and Engle (2006) more closely than our young adult group. Based on these results, it seems likely that for this age group, primary memory was represented in the short-term memory list lengths 1-2 and that secondary memory was represented by performance in short-term memory list lengths 4-7, as well as working memory list lengths 2-4. The working memory list length 1 condition was somewhat ambiguous

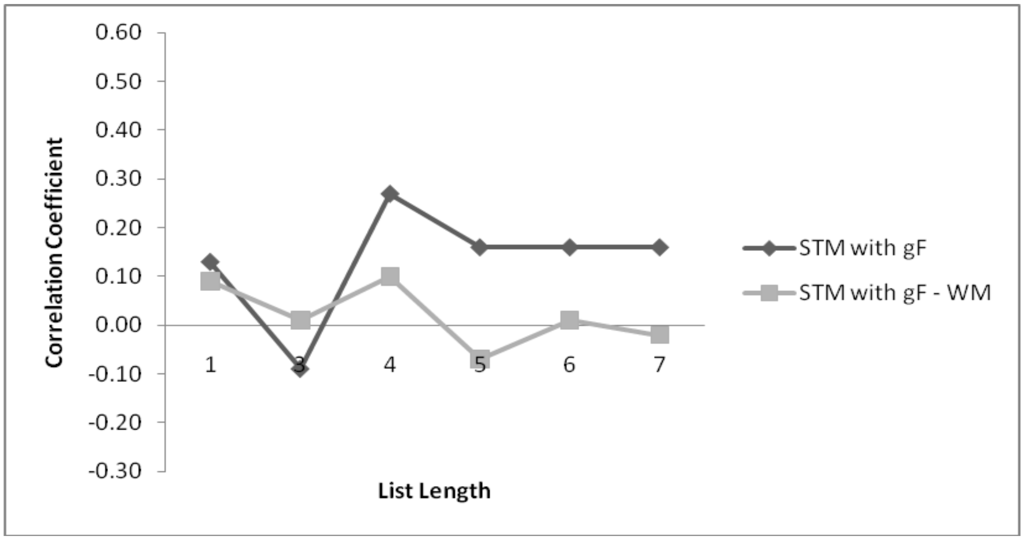

Figure 8. Correlations between proportion-correct for short-term memory list length conditions and fluid intelligence for the adult group

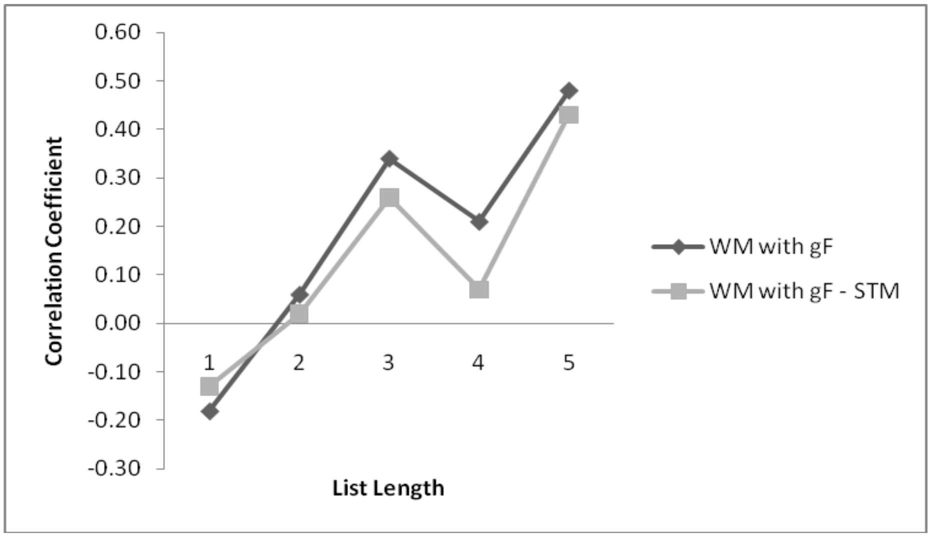

Figure 9. Correlations between proportion-correct for working memory list length conditions and fluid intelligence for the adult group

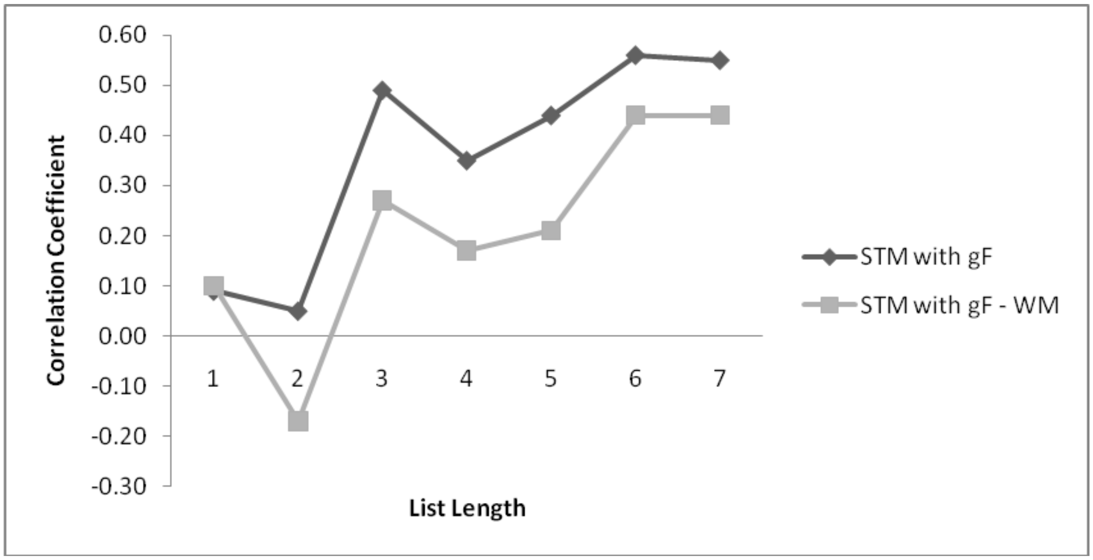

Figure 10. Correlations between proportion-correct for short-term memory list length conditions and fluid intelligence for the 8-9 year-old group

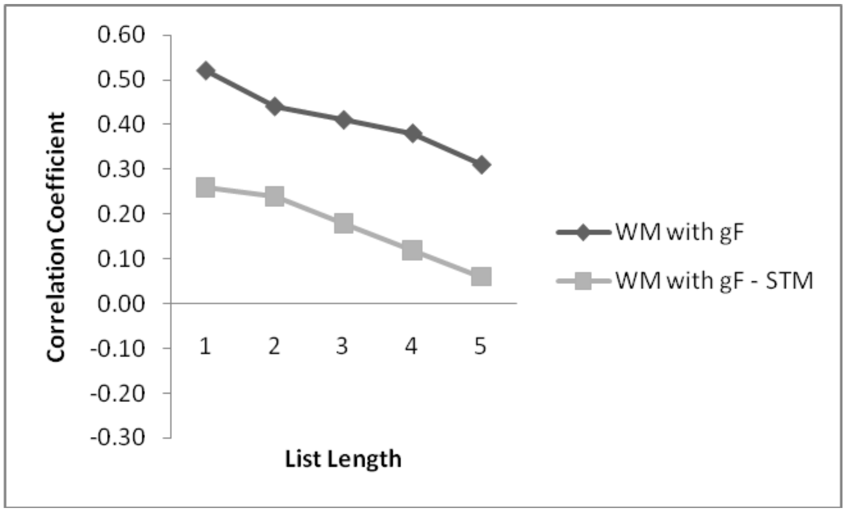

Figure 11. Correlations between proportion-correct for working memory list length conditions and fluid intelligence for the 8-9 year-old group

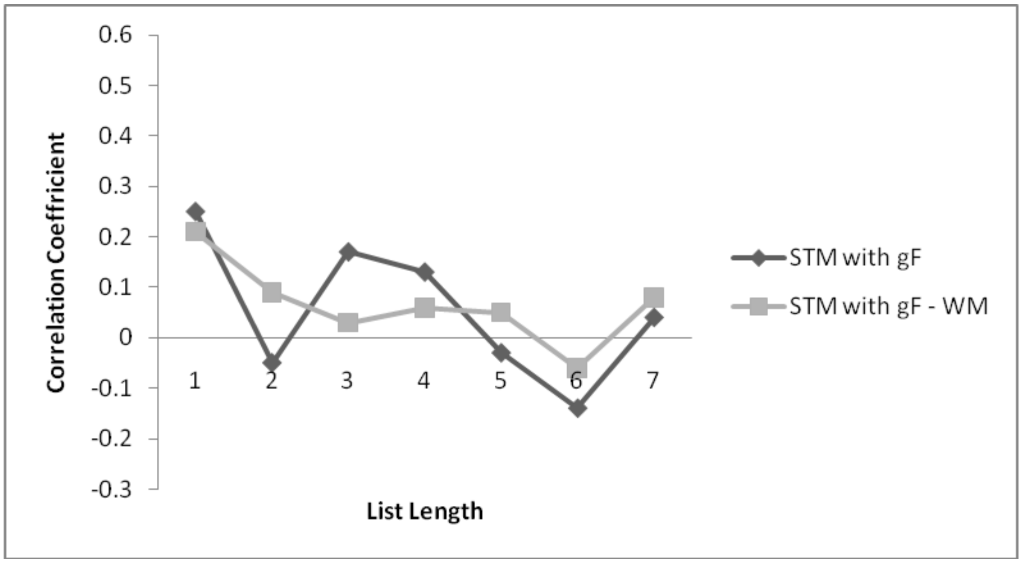

Figure 12. Correlations between proportion-correct for short-term memory list length conditions and fluid intelligence for the 10-11 year-old group

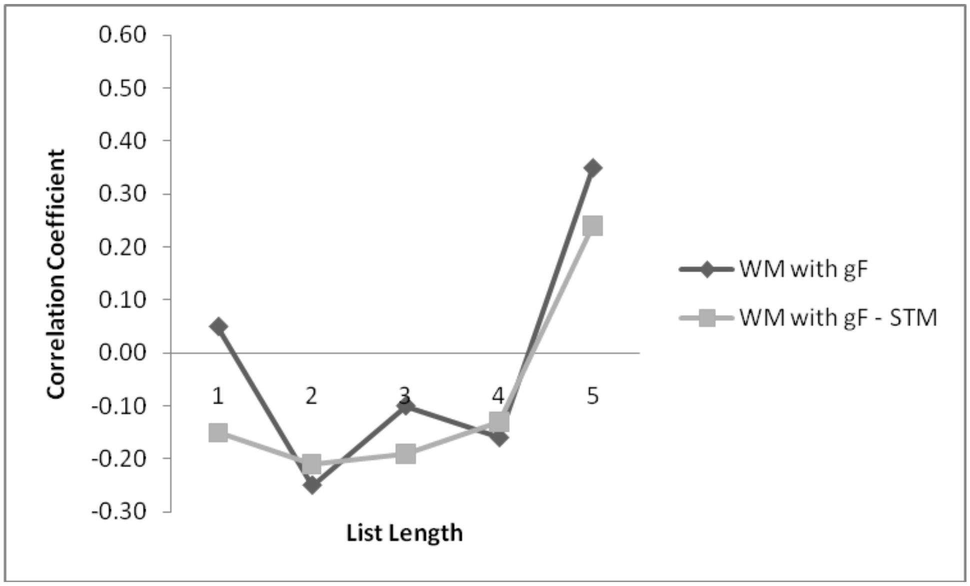

Figure 13. Correlations between proportion-correct for working memory list length conditions and fluid intelligence for the 10-11 year-old group

because it did show almost ceiling performance (97% correct) but it also had a high correlation with intelligence. According to the Unsworth and Engle (2006) model, the list length 1 condition for both the short-term and working memory tasks should tap primary memory only. Another ambiguous condition was the working memory list length 5. This condition did not seem to have floor performance (26% correct, *SD* = 0.15), but it did not show a significant correlation with intelligence. Like Unsworth and Engle (2006), the short-term memory list length 3 condition was also removed from further analyses because it was likely that for some participants in this age group, the condition only measured primary memory, but for others, it likely measured primary and secondary memory contributions.

The relationships between fluid intelligence and the short-term and working memory task list length conditions were much smaller in the 10-11 year-old group. The only zero-order correlation that was significant was the one with the working memory task list length 5 condition ($r = 0.35$, $p < 0.05$). When the short-term memory task list lengths were partialled out of the correlation, that relationship was no longer significant ($r = 0.24$, $p > 0.05$). This correlation analysis did not differentiate between which list lengths are tapping secondary memory in the way demonstrated by Unsworth and Engle (2006). Therefore, we used the same division points as Unsworth and Engle (2006) used for their adult group to separate the short-term memory list length conditions into those that reflect primary and secondary memory. These divisions did match the findings of the proportion accurately recalled in each list length condition. The short-term memory list lengths 1-3 had near perfect recall, with accuracy falling after that point. With the ambiguity of list length 4 for some participants, we excluded that list length from the multiple regression analysis, which is discussed in more detail after the scope of attention analyses.

Scope of Attention

The scope of attention measures, running memory span and visual array comparison task, were examined to better understand how this factor related to the primary memory factor and the fluid intelligence factor. The means and standard deviations for the scope of attention composite measure were presented in Tables 1-3 for each age group separately (the individual task means and standard deviations were presented in Appendix D). A one-way ANOVA was conducted on the scope of attention composite scores to examine the age group differences, followed with a Bonferroni correction to the post-hoc comparison. There was a significant main effect of age group, $F(2, 120) = 39.78$, $p < 0.01$. The two child groups were not significantly different, but the young adult group had a significantly higher scope of attention capacity than the two younger groups.

We also compared the patterns of correlations with scope of attention and the different list length conditions. With Tables 1-3, the raw correlations for each age group were displayed, but we also wanted to examine the correlations between fluid intelligence, the different list length conditions and importantly, the scope of attention for the entire sample with age as a factor and with age partialled out (see Table 5). After age was partialled out, the scope of attention measure maintained most of the significant correlations except with the list length 2 and 3 conditions from the short-term memory task. In Table 1, the scope of attention measure significantly correlated with fluid intelligence and the longer list lengths of both the short-term memory and working memory tasks for the young adults. In Table 2, there were fewer significant correlations between the scope of attention and the list length conditions with correlations with the longer list lengths in the working memory task being significant. We also examined the correlations between the scope of attention and the primary memory capacity (as reported in Table 4). In the adult group, the correlation was $r = .38$, $p < 0.01$. In the 8-9 year-old group, $r = .43$, $p < 0.01$. In the 10-11 year-old group, $r = .04$, $p > 0.05$. These correlations are likely larger than the correlations between the short list length conditions and the scope of attention because of the greater variability present in the primary memory capacity estimates than in the short list length conditions. However, these correlations are much lower than one might expect with two measurements of the same construct.

Table 5. The Correlations for Age, Short-term Memory List Length Conditions, Working Memory List Length Conditions, Fluid Intelligence and Scope of Attention

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. age	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2. STMLL1	0.03	--	0.15	0.04	0.22*	0.08	0.24**	0.21*	0.11	0.04	0.14	0.14	0.18*	0.12	0.07
3. STMLL2	0.25**	0.15	--	-0.02	0.14	0.17	0.03	0.07	-0.10	0.29**	0.22*	0.25**	0.13	0.05	0.14
4. STMLL3	0.33**	0.05	0.07	--	0.43**	0.33**	0.35**	0.24**	0.48**	0.34**	0.38**	0.24**	0.31**	0.37**	0.16
5. STMLL4	0.56**	0.20*	0.25**	0.52**	--	0.56**	0.46**	0.36**	0.18	0.26**	0.45**	0.26**	0.39**	0.37**	0.37**
6. STMLL5	0.71**	0.08	0.30**	0.45**	0.73**	--	0.67**	0.59**	0.14	0.33**	0.47**	0.33**	0.42**	0.35**	0.41**
7. STMLL6	0.72**	0.18*	0.20*	0.47**	0.67**	0.84**	--	0.72**	0.18	0.24**	0.45**	0.40**	0.38**	0.36**	0.31**
8. STMLL7	0.73**	0.16	0.23*	0.40**	0.61**	0.80**	0.87**	--	0.13	0.17	0.36**	0.42**	0.39**	0.35**	0.34**
9. WMLL1	0.14	0.11	-0.06	0.50**	0.22*	0.20*	0.23*	0.20*	--	0.24**	0.19*	0.02	0.00	0.20*	0.06
10.WMLL2	0.36**	0.05	0.35**	0.41**	0.40**	0.47**	0.41**	0.37**	0.27**	--	0.43**	0.47**	0.34**	0.26**	0.27**
11. WMLL3	0.53**	0.14	0.32**	0.48**	0.61**	0.65**	0.64**	0.59**	0.24**	0.53**	--	0.57**	0.63**	0.40**	0.34**
12. WMLL4	0.59**	0.13	0.34**	0.37**	0.50**	0.61**	0.65**	0.66**	0.10	0.57**	0.71**	--	0.64**	0.32**	0.30**
13. WMLL5	0.48**	0.18	0.23*	0.41**	0.55**	0.60**	0.58**	0.59**	0.07	0.45**	0.72**	0.73**	--	0.48**	0.38**
14. gF	0.59**	0.12	0.18*	0.48**	0.58**	0.61**	0.62**	0.63**	0.24**	0.41**	0.59**	0.56**	0.62**	--	0.40**
15. Scope	0.56**	0.08	0.25**	0.31**	0.57**	0.64**	0.59**	0.60**	0.13	0.41**	0.53**	0.53**	0.54**	0.60**	--

Note: * indicates $p < 0.05$; ** indicates $p < 0.01$; LL stands for list length; STM stands for short-term memory; WM stands for working memory; gF stands for fluid intelligence. The raw correlations are below the diagonal and the correlations with age partialled out are above the diagonal.

Multiple Regression Analyses

The primary purpose of performing multiple regression analyses with variance partitioning methods with the current data was to examine the contribution of primary memory, secondary memory, and the scope of attention to fluid intelligence, without any pre-existing theoretical predictions as is necessary with step-wise regression analyses. This type of analysis, described in great detail by Chuah and Mayberry (1999), allows the researcher to divide the variance accounted for by the group of independent variables into the amount of variance uniquely and in shared manners predicting the criterion variable. For this study, the main predictor variables of interest were age, primary memory performance (defined as the short-term memory list lengths with near perfect serial recall performance), secondary memory performance (measured by the short-term memory long list lengths and the working memory list lengths greater than 1), and the scope of attention performance (a composite variable from the auditory running span average number of items recalled in correct serial position and the visual array comparison task performance calculated with Cowan's *k* score for capacity). The criterion variable was the composite *z* score from the three measures of fluid intelligence.

We started by conducting a simultaneous regression with the five factors of interest. Table 6 shows the outcome of that regression analysis. This analysis indicated that the working memory list lengths and the scope of attention were the only two significant factors.

Table 6. Simultaneous Regression for the Entire Sample with Fluid Intelligence as the Criterion Variable

Variable	*B*	*t*	sr^2	R^2	*F*
Age	0.141	1.43	0.01		
STM LL1-2	-0.029	-0.44	0.00		
STM LL 5-7	0.204	1.73	0.01		
WM LL 2-5	0.300	3.10**	0.04		
Scope	0.215	2.50*	0.02	0.53	26.84**

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; Age represents age in years; LL stands for list lengths; STM stands for short-term memory; WM stands for working memory; Scope is the composite score for the scope of attention tasks

With the working memory list lengths and the scope of attention playing the largest role in predicting fluid intelligence, it seemed best to perform the variance-partitioning regression procedure with each age group separately to see how these predictor variables might contribute differently to fluid intelligence depending on the age group. With that in mind, some changes were made for the predictor variables for each age group based on the findings of the correlation and partial correlation analyses for each age group. Some of the list length conditions for some of the age groups were not solely tapping into primary memory or secondary memory ability, so we made some adjustments to those factors for the age groups based on those outcomes. For the 8-9 year-olds, we combined list lengths 1 and 2 from the short-term memory task to represent primary memory performance, we then combined list lengths 4 through 7 from the short-term memory task to represent the recall from secondary memory in that task, and finally, we combined the list lengths 2-4 from the working memory task to represent secondary memory in that task. For the 10-11 year-olds, we matched most of the adult factors by combining the short-term memory list lengths 1-3 for the primary memory factor and list lengths 5-7 for the short-term memory secondary memory factor. We then combined performance from the working memory task list lengths 2-5 to represent the other secondary memory factor. The only difference in the factors between the 10-11 year-old group and the adult group was in the working memory list lengths for the adults. The list length 2 performance was very high for the adults, possibly due to the fact that the tasks were designed with children in mind. Given that this list length was ambiguous, we decided to omit it from the adult multiple regression analyses in the same way that the short-term memory list length 4 was removed from the multiple regression analyses. We performed the multiple regression analyses in each age group without the scope of attention composite factor first, to replicate the analysis performed by Unsworth and Engle (2006) and then performed it with the scope of attention factor. By including the scope of attention, we were able to examine the hypothesis of Cowan et al. (2005) that the scope of attention is an important factor in both working memory performance and the link shared between working memory and fluid intelligence.

Table 7 shows the results of the simultaneous regression for the adult group. The overall variance accounted for by this group of factors ($R^2 = 0.162$) was smaller than the variance accounted for by the Unsworth and Engle (2006) study ($R^2 = 0.283$). Like the Unsworth and Engle (2006) findings, we also show that working memory performance was a significant predictor of intelligence but unlike their findings, we were unable to show that the long list lengths in the short-term memory task were a significant predictor. We followed the simultaneous regression by a series of variance-partitioning regression analyses to indicate unique and shared variance accounted for by our factors. These analyses can be seen in Table 8 and the partialled variance in Figure 14.

This analysis did not replicate the findings of Unsworth and Engle (2006). Their variance-partitioning regression analyses indicated that the working memory task list lengths and the long short-term memory list lengths each contributed some unique variance but the shared variance between the working memory task list lengths and the long short-term memory list lengths contributed the most predictive variance to fluid intelligence. This supported their hypothesis that both of these factors measured retrieval from secondary memory, which they state was the main reason that working memory tasks relate strongly to fluid intelligence. In the current analyses, the two main predictors of fluid intelligence were the unique variance from the

Table 7. The Simultaneous Regression Analysis Predicting Intelligence for the Adult Group

Variable	*B*	*t*	*sr*²	*R*²	*F*
STM LL 1-3	0.014	0.10	0.00		
STM LL 5-7	0.006	0.04	0.00		
WM LL 3-5	0.397	2.72**	0.13	0.162	3.15*

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; LL stands for list lengths; STM stands for short-term memory; WM stands for working memory

Table 8. The R^2 Values produced from Variance-Partitioning Regression Analyses Predicting Intelligence in the Adult Group

Predictor Variables	*R*²	*F*
WM3-5, STM1-3, STM5-7	0.162	3.15*
WM3-5, STM1-3	0.162	4.82*
WM3-5, STM5-7	0.162	4.82*
STM1-3, STM5-7	0.035	0.92
WM3-5	0.161	9.82**
STM1-3	0.009	0.45
STM5-7	0.033	1.73

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; LL stands for list lengths; STM stands for short-term memory; WM stands for working memory

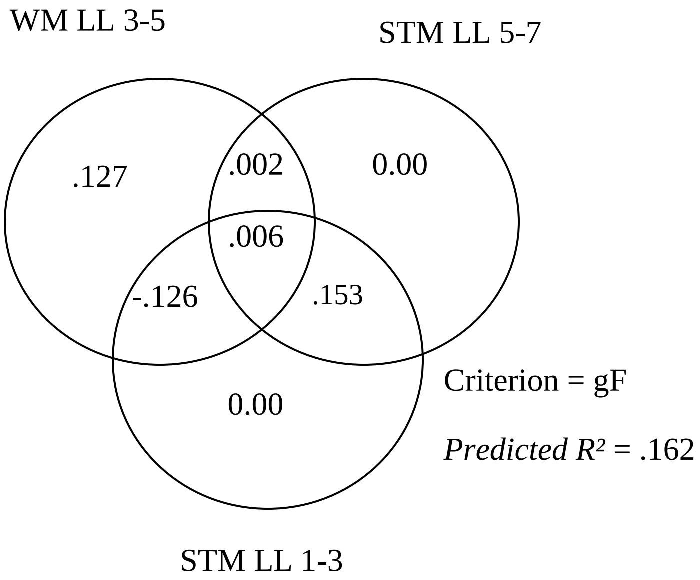

Figure 14. Unique and Shared Variance from Short-term Memory List Length Conditions, and Working Memory List Length Conditions Predicting Fluid Intelligence

working memory list lengths and the shared variance between the two short-term memory factors. To further replicate Unsworth and Engle, we substituted an individual measure of primary memory for the short-term memory list lengths 1-3 factor. The individual measure of primary memory was calculated by finding the highest list length which was perfectly recalled as well as all of the previous list lengths. This change only increased the overall explained variance by .3% taking it from 16.2% to 16.5% and did not change any of the relationships within the variance-partitioning regression analyses.

An important aspect to note about this variance partitioning regression analysis is the finding of a negative amount of variance accounted for by the shared factor between the list lengths 1-3 in the short-term memory task and the list length conditions for the working memory task. On the face of it, negative variance accounted for seemed nonsensical but this is actually a relatively common issue with multiple regression analyses, called suppression (Smith, Ager, & Williams, 1992). With classic suppression, as in this case, one or more factors have a negative amount of variance due to another variable's contributing variance being increased by the inclusion of other variables. Simply put, the overall variance for the regression analyses for each factor and each combination of factors is less than the variance for one or more factors individually. This leads to the individual factors contributing more variance than could be contributed by the model together. In this model, it seemed likely that the working memory list lengths 3-5 factor was able to contribute more to the model with the other factors included than it did independently and thus it “stole” variance from the shared working memory and short-term memory list lengths 1-3 factor, leaving that factor, which should have been close to zero, into a negative number. This suppression is usually caused by including factors that are strongly correlated and therefore, have multi-colinearity. While some researchers insist on removing variables from multiple regression models for either not providing significant variance independently or because they are correlated with the other factors, it has been suggested that this removal process can distort the knowledge gained by leaving the variables in the model, especially in the case of suppression (Shieh, 2006). Classic suppression was present in all of the significant variance-partitioning analyses that we conducted, likely due to the short-term memory short list length factor having a low, non-significant correlation with fluid intelligence, but this factor helps other factors contribute more variance than should be possible.

We followed these multiple regression analyses with one in which we added the scope of attention factor. This scope of attention factor (Cowan et al., 2005) is theoretically very similar to primary memory but the two factors are measured in different manners. By including this factor, we were able to test the practical similarity between the two factors as well as testing the hypothesis of Cowan et al. (2005) that the scope of attention contributes significantly to fluid intelligence and the relationship between working memory task performance and fluid intelligence. See Table 9 for the simultaneous regression analysis with all four factors in the adult group. See Table 10 and Figure 15 for the results of the variance-partitioning regression analyses with the scope of attention factor.

Table 9. The Simultaneous Regression Analysis with a Scope of Attention Factor Predicting Intelligence for the Adult Group

Variable	*B*	*t*	*sr*²	*R*²	*F*
STM LL1-3	0.059	0.45	0.00		
STM LL 5-7	-0.136	-0.89	0.01		
WM LL 3-5	0.320	2.25*	0.08		
Scope	0.354	2.44*	0.09	0.254	4.09**

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; LL stands for list lengths; STM stands for short-term memory; WM stands for working memory

Table 10. The R^2 Values produced from Variance-Partitioning Regression Analyses with the Scope of Attention Factor Predicting Intelligence in the Adult Group

Variables	*R*²	*F*
STM 1-3, STM 5-7, WM 3-5, Scope	0.254	4.09**
STM 1-3, WM 3-5, Scope	0.242	5.21**
STM 1-3, STM 5-7, Scope	0.176	3.48*
STM 5-7, WM 3-5, Scope	0.251	5.48**
STM 1-3, STM 5-7, WM 3-5	0.162	3.15*
STM 1-3, Scope	0.175	5.29**
WM 3-5, Scope	0.241	7.93**
STM 5-7, Scope	0.167	5.01*
STM 1-3, WM 3-5	0.175	5.29**
STM 1-3, STM 5-7	0.035	0.92
WM 3-5, STM 5-7	0.162	4.82*
Scope	0.167	10.21**
STM 1-3	0.009	0.45
STM 5-7	0.033	1.73
WM 3-5	0.161	9.82**

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; LL stands for list lengths; STM stands for short-term memory; WM stands for working memory

In the four factor variance-partitioning regression analyses, the overall amount of variance accounted for increased from 16.2% to 25.4%. The reason for the increased variance was clearly the unique variance associated with the scope of attention as well as some of the

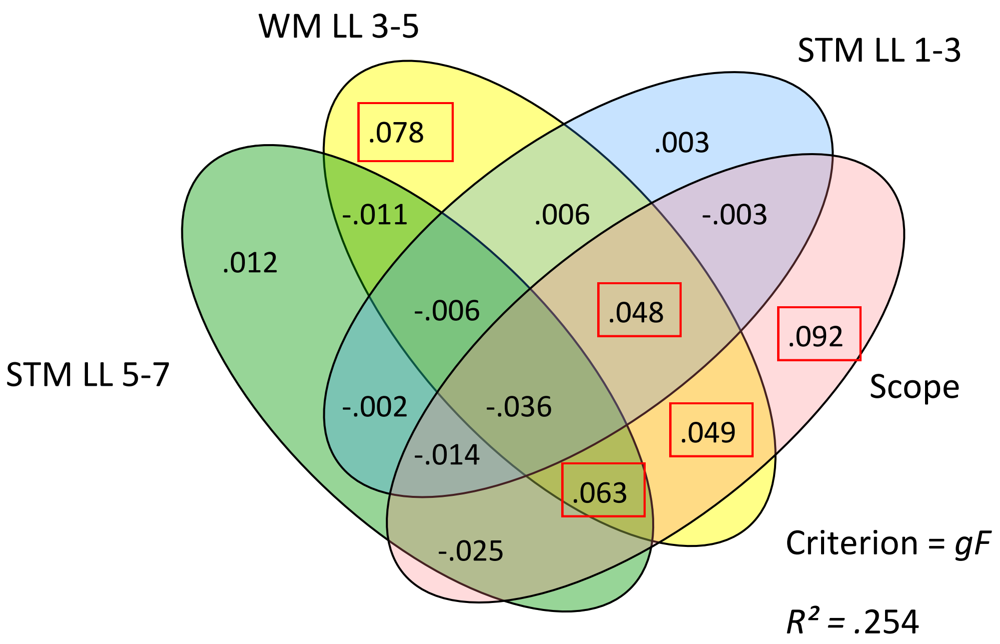

Figure 15. Unique and Shared Variance from Short-term Memory List Length Conditions, and Working Memory List Length Conditions, and Scope of Attention Predicting Fluid Intelligence for Adult Group

shared variance with scope of attention and the other three factors. Instead of seeing a clear distinction between primary and secondary memory in this analyses, there seems to be a working memory factor and a scope of attention factor that both contributed to fluid intelligence. It was difficult to see which factors then reflect primary memory in its theoretical lack of a relationship with fluid intelligence.

We conducted very similar simultaneous and variance-partitioning regression analyses with the 8-9 year-old group. We began with the simultaneous regression analysis for the three factors: short-term memory list lengths 1-2, short-term memory list lengths 4-7, and working memory list lengths 2-4. This regression analysis is depicted in Table 11.

Table 11. The Simultaneous Regression Analysis Predicting Intelligence for the 8-9 Year-old Group

Variable	*B*	*t*	*sr*^{2}	*R*^{2}	*F*
STM LL 1-2	-0.05	-0.34	0.00		

(Table 11 cont.)

STM LL 4-7	0.41	2.25*	0.10		
WM LL 2-4	0.25	1.33	0.04	0.339	5.48**

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; LL stands for list lengths; STM stands for short-term memory; WM stands for working memory

Table 12. The R^2 Values produced from Variance-Partitioning Regression Analyses with the Scope of Attention Factor Predicting Intelligence in the 8-9 Year-old Group

Variables	R^2	*F*
STM 1-2, STM 4-7, WM 2-4	0.339	5.48**
WM 2-4, STM 1-2	0.235	5.06*
WM 2-4, STM 4-7	0.337	8.39**
STM 1-2, STM 4-7	0.303	7.18**
WM 2-4	0.233	10.33**
STM 1-2	0.007	0.24
STM 4-7	0.303	14.77**

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; STM stands for short-term memory; WM stands for working memory

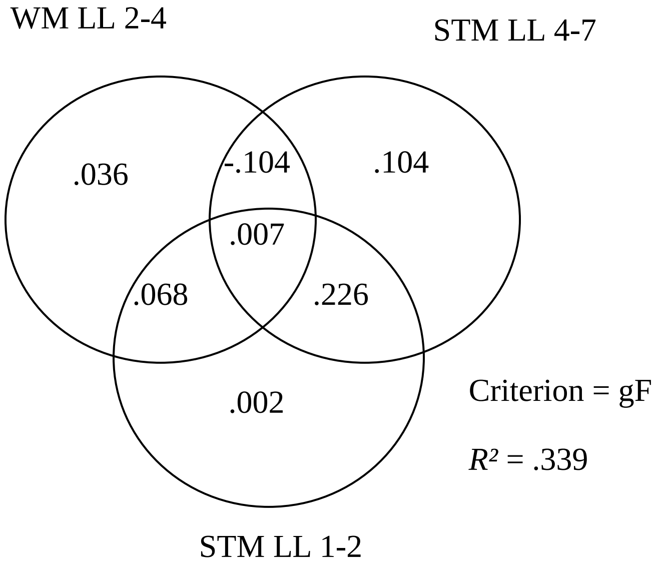

Figure 16. Unique and Shared Variance from Short-term Memory List Length Conditions, and Working Memory List Length Conditions Predicting Fluid Intelligence for the 8-9 Year-old Group

Unlike the adult simultaneous regression, the only factor in the 8-9 year-old group with a significant *t* value was the longer short-term memory list lengths rather than the working memory list length conditions. The amount of variance accounted for by this regression was also larger than the same regression for the adult group (16.2% compared with 33.9% for this age group). We followed this with the variance-partitioning regression analyses (see Table 12) to determine the unique and shared variances (see Figure 16 for the Venn Diagram).

These analyses, like the simultaneous regression analysis, yielded very different outcomes than the adult group analyses. Whereas, the adult group's working memory factor and the shared short-term memory partition were the main contributors, the 8-9 year-old group's shared short-term memory factor was the main contributor, with smaller contributions from the shared short-term memory list lengths 1-2 factor and working memory factor and from the longer short-term memory list length factor alone. This analysis once again calls into question the hypothesis of Unsworth and Engle (2006) that secondary memory, which can be measured in the long short-term memory trials or during the working memory task, is the only factor to contribute to fluid intelligence. Their claims were not made specifically with children in mind, but in terms of the generality of the proposed model, the same model in adults should be seen in children to uphold its validity. De Alwis et al.'s (2009) findings supported the Unsworth and Engle (2006) model in children but our findings do not support the generalization of the model.

Then, the scope of attention factor was added to the analyses. Table 13 shows the simultaneous regression analysis for the four factors with only the long short-term memory list length factor contributing a significant amount of variance. This analysis was followed by the variance-partitioning regression analyses (seen in Table 14 and Figure 17). Adding the scope of attention factor only increased the variance accounted for by 2.4%, which is a much smaller percentage than when the scope of attention was added to the other 3 factors in the adult group. These analyses indicated that the shared factors with the long short-term memory factor as well as the long short-term memory factor alone accounted for the greatest amount of variance. The greatest amount of variance was predicted by the shared variance between the long short-term memory factor, the working memory factor, and the scope of attention factor. Given the similarity between the theoretical definition of the scope of attention and it's similarity to the definition of primary memory, it seems unusual for a shared component of those three factors to account for the most variance in fluid intelligence.

Table 13. The Simultaneous Regression Analysis with the Scope of Attention Factor Predicting Intelligence for the 8-9 Year-old Group

Variables	*B*	*t*	sr^2	R^2	*F*
STM 1-2	-0.07	-0.49	0.00		
STM 4-7	0.40	2.21*	0.10		
WM 2-4	0.18	0.95	0.02		
Scope	0.17	1.08	0.02	0.363	4.42**

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; STM stands for short-term memory; WM stands for working memory

Table 14. The R^2 Values produced from Variance-Partitioning Regression Analyses with the Scope of Attention Predicting Intelligence in the 8-9 Year-old Group

Variables	R^2	*F*
STM 1-2, STM 4-7, WM 2-4, Scope	0.36	4.42**
STM 1-2, WM 2-4, Scope	0.26	3.81*
STM 1-2, STM 4-7, Scope	0.35	5.61**
STM 4-7, WM 2-4, Scope	0.36	5.96**
STM 1-2, STM 4-7, WM 2-4	0.34	5.48**
STM 1-2, Scope	0.12	2.30
WM 2-4, Scope	0.26	5.77**
STM 4-7, Scope	0.34	8.57**
STM 1-2, WM 2-4	0.24	5.06**
STM 1-2, STM 4-7	0.30	7.18**

(Table 14 cont.)

WM 2-4, STM 4-7	0.34	8.39**
Scope	0.12	4.75**
STM 1-2	0.01	0.24
STM 4-7	0.30	14.77**
WM 2-4	0.23	10.33**

Note: * indicates $p < 0.05$, ** indicates $p < 0.01$; STM stands for short-term memory; WM stands for working memory

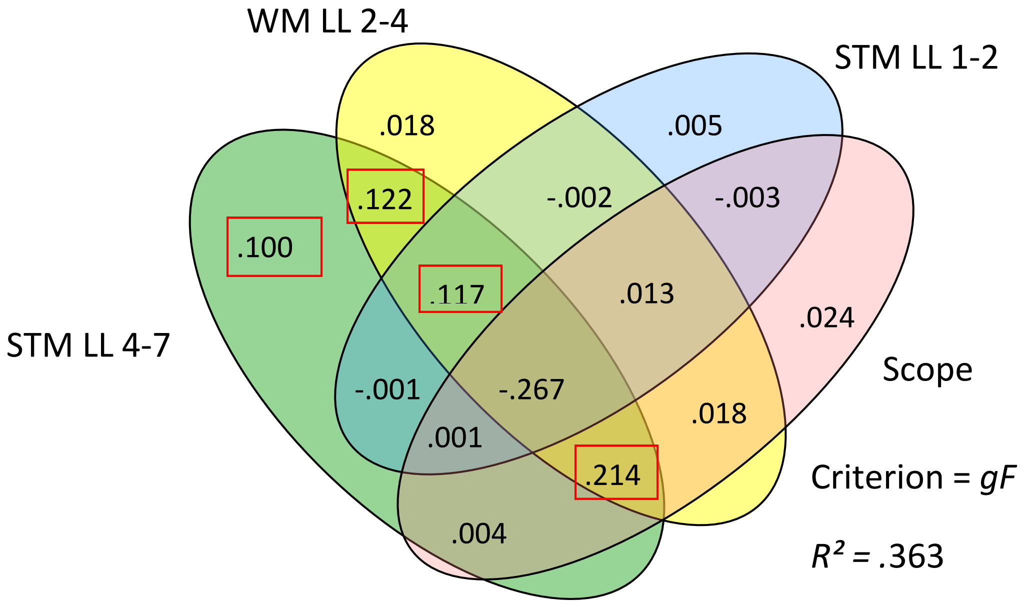

Figure 17. Unique and Shared Variance from Short-term Memory List Length Conditions, and Working Memory List Length Conditions, and Scope of Attention Predicting Fluid Intelligence for 8-9 Year-old Group

Finally, the 10-11 year-old group's data were analyzed similarly to the adult group and the 8-9 year-old group. We began with a simultaneous regression with three factors: short-term memory short list lengths, short-term memory long list lengths, and working memory list lengths. Given the general lack of correlations with the list length conditions in the memory tasks and fluid intelligence, it was not surprising that this regression analysis was not significant (see Table 15).

Table 15. The Simultaneous Regression Analysis Predicting Intelligence for the 10-11 Year-old Group

Variables	*B*	*t*	*sr*²	*R*²	*F*
STM 1-3	0.33	1.62	0.08		
STM 5-7	-0.11	-0.57	0.01		
WM 2-5	-0.17	-0.86	0.02	0.085	0.93

Note: STM stands for short-term memory; WM stands for working memory

After this analysis failed to indicate a significant predictor variable for fluid intelligence, we added the scope of attention factor to the other three to examine whether that might produce a significant model (See Table 16). While the *R*² did indicate that more variance was explained, none of the four factors reached significance nor did the model as a whole.

Table 16. The Simultaneous Regression Analysis with the Scope of Attention Factor Predicting Intelligence for the 10-11 Year-old Group

Variables	*B*	*t*	*sr*²	*R*²	*F*
STM 1-3	0.36	1.76	0.09		
STM 5-7	-0.16	-0.83	0.02		
WM 2-5	-0.20	-0.99	0.03		
Scope	0.22	1.22	0.04	0.129	1.08

Note: STM stands for short-term memory; WM stands for working memory

Differences in Findings Based on Scoring Differences

In addition to performing analyses based on those of Unsworth and Engle (2006), we also explored how different scoring methods for our short-term and working memory tasks could impact their relationship with fluid intelligence. An article by Unsworth and Engle (2007b) brings to light the importance of scoring procedures used for short-term and working memory tasks in their ability to predict fluid intelligence. These differences in scoring procedures impact the predictions that we can make here because in certain cases, it has been found that working memory tasks, but not short-term memory tasks, predict fluid intelligence (Engle, Tuholski et al.,

1999) but in the reanalysis of Engle, Tuholski et al., Unsworth and Engle (2007b) found that both tasks together strongly predict fluid intelligence but not individually. In one of the few child studies examining how short-term memory and working memory relate to fluid intelligence, Cowan et al. (2005) found that both were good predictors for younger children but only working memory performance was predictive for their older children and adult samples, similar to the findings of Engle, Tuholski et al. Interestingly, Cowan et al. (2005) used a slightly different scoring procedure than Engle, Tuholski et al. (1999) or Unsworth and Engle (2007b).

Engle, Tuholski et al. (1999) used a method of scoring the tasks known as absolute scoring. This method scores each trial of the working memory and short-term memory task as correct if all items in that trial were recalled in correct serial order, but incorrect if any one item is incorrect (wrong item or wrong placement). Then a sum is taken of the total number of items in each of the perfectly recalled trials across each list length condition. The scoring procedure used by Unsworth and Engle (2007b) was called the proportion correct scoring. This method counts each item correct if it is in the correct serial position, whether the entire list is correct or not. Then the total number of correct items is divided by the total number of items during the trials at any given list length and then these proportions are averaged to make a single score for the participant. Cowan et al. (2005) utilized two different scoring methods but they state that the second produced higher correlations so their results were reported from the second method. The first method is what they call the “traditional scoring method” for spans and identifies the highest list length at which at least 50% (in our case 2 out of 4) of the trials were recalled in correct serial order. The second method is called the “maximal number correct” scoring and it averages the total number of items in correct serial position for each list length condition and the list length condition with the highest average of items correct uses its average score as the span.

Another method of span calculation that has been used is known as “cumulative span” (Elliott, 2002) and is calculated by assigning .25 for each correct trial and then adding up the total score. This score then assigns 1 point for each correctly recalled list length because there were four trials at each list length. Because of the differences in previous findings, performing these analyses could have indicated that both children’s and adults’ short-term memory and working memory performance are good predictors of fluid intelligence. See Table 17 for the Pearson *r* correlations for each task in each age group with the five different methods previously described.

While there does not seem to be many systematic differences between the resulting correlation coefficients for the different methods, there are some important findings. First of all, the adult group has many more significant correlations between task performance and fluid intelligence for the working memory tasks than for the short-term memory performance. However, in the 8-9 year-old group, the significant correlations are almost equal between the short-term memory tasks and the working memory tasks. The one scoring method that seems to stand apart is the Maximal Number Correct Scoring Technique of Cowan et al. (2005). This technique produced one strong correlation that the other methods did not indicate, the correlation between the listening span task in the adults and fluid intelligence. The technique also did not show correlations that were found using other techniques in the 8-9 year-old group: the correlations for the digit span task, the counting span task, and the listening span task.

Conway et al. (2005) examined the differences between scoring techniques for working memory tasks only. They identified some different techniques that are commonly utilized: absolute span scoring, all-or-nothing versus partial scoring, and unit-scoring versus load scoring. The traditional scoring method and the maximal number correct scoring that we used would both be considered absolute span scoring. Absolute scoring and cumulative span scoring both use all

Table 17. Correlations between Different Methods of Scoring Memory Tasks and Fluid Intelligence

Adults		Absolute Scoring	Proportion Correct Scoring	Traditional Scoring Method	Maximal Number Correct	Cumulative Span
STM Tasks	Digit Span	0.14	0.05	0.31*	0.11	0.13
	Word Span	0.32*	0.24^	0.21	0.24^	0.34*
WM Tasks	Counting Span	0.40**	0.37**	0.28*	0.47**	0.41**
	Listening Span	0.23^	0.21	0.18	0.36**	0.21
8-9 Year Olds						
STM Tasks	Digit Span	0.47**	0.54**	0.40*	0.22	0.45**
	Word Span	0.53**	0.53**	0.46**	0.46**	0.53**
WM Tasks	Counting Span	0.33*	0.31^	0.36*	0.25	0.38*
	Listening Span	0.46**	0.46**	0.50**	0.06	0.48**
10-11 Year Olds						
STM Tasks	Digit Span	-0.09	-0.15	-0.13	0.07	-0.08
	Word Span	0.19	0.14	0.21	0.02	0.22
WM Tasks	Counting Span	-0.13	0.01	-0.03	-0.07	-0.15
	Listening Span	-0.25	0.04	-0.28	-0.10	-0.25

Note: ^ indicates $p < 0.10$; * indicates $p < 0.05$, ** indicates $p < 0.01$; STM stands for short-term memory; WM stands for working memory; Adult $n = 53$, 8-9 year-olds $n = 36$, 10-11 year-olds $n = 34$

or none scoring; whereas, proportion correct scoring utilizes partial scoring. The absolute scoring, proportion correct scoring and cumulative span scoring also incorporate unit-scoring, by not giving more weight to longer list lengths than the shorter list lengths. In terms of reliability of the scoring techniques, Conway et al. (2005) found that the partial scoring was more reliable than the all or nothing scoring and additionally that the unit scoring was slightly more reliable than load scoring. They did not calculate the reliabilities for absolute span scoring although they pointed out several potential flaws with using the span scoring technique. These reasons include extraneous variables that could affect performance on longer list lengths, such as length of the stimuli or display time for different stimuli, and also the fact that after the participant fails to complete the trials at a given list length, the task is ended or the longer list length performances are not considered at all in the score.

According to this study, the most reliable scoring technique that we utilized was the proportion scoring technique. However, this technique was not completely suited to our main goals, since we were interested in the span capacities for the short-term and working memory tasks to be able to calculate the capacities of the primary memory and secondary memory. The cumulative span measure that we used did not have all of the flaws of the absolute span scoring that Conway et al. (2005) believed was more prone to reliability issues. First of all, our participants completed list length conditions much longer than the possible maximum capacity for both the short-term and working memory tasks. Secondly, some span scores create an integer span (a whole number) and the cumulative span increases the sensitivity of the measure because each additional list length longer than the more traditional span added .25 to the total score.

DISCUSSION

The goals of the current study were to measure primary and secondary memory in both children and adults, to examine how these two types of memory differed between the age groups. Another goal was to test the hypotheses of Unsworth and Engle (2006) regarding the characteristics of these two different constructs and their relationship to fluid intelligence. Unsworth and Engle (2006) made multiple predictions regarding primary and secondary memory and the way that these constructs should be measured by short-term and working memory tasks. Finally, the last major goal was to examine why short-term memory task performance sometimes predicts fluid intelligence (in children, Cowan et al. 2005) but other times only working memory task performance was a good predictor of intelligence (in adults, Engle, Tuholski et al., 1999). To better understand this relationship, we included the scope of attention as a factor, which Cowan et al. (2005) described in a manner similar to the definition given for primary memory (Unsworth & Engle, 2006), and we explored different methods of calculating performance from short-term and working memory tasks.

Assumptions and Development of Primary and Secondary Memory

First, we created a table (Table 4) to facilitate direct comparisons of performance on short-term and working memory tasks, as well as primary memory capacity and the retrieval capacity from secondary memory. For the most part, we found that the assertion that short-term memory capacity is based on adding together primary memory capacity and the average retrieval from secondary memory to be inaccurate. For all of the age groups, the short-term memory span was higher than the addition of primary and secondary memory capacities, with the difference being smaller in the older groups and larger in the youngest group. The assertion that working memory capacity could be measured by adding average retrieval from secondary memory to the assumed 1 item in primary memory, was also inaccurate. For the 8-9 year-old group, the estimate was higher than the actual working memory span. For the 10-11 year-old group, the estimate was almost identical to the actual working memory span. For the young adult group, the estimate was less than the actual working memory span. Thus, it seems that there is an additional factor assisting in short-term memory capacity. The calculation of secondary memory plus 1 item for working memory seemed to overestimate the ability for the youngest age group and underestimate the ability for the young adult group. Perhaps in the young adults, primary memory is able to assist with more than 1 item in secondary memory (Shelton et al., 2010).

Our results also differed from the published results of Unsworth and Engle (2007b). Their study compared high and low span adults for their capacity of primary memory and the average retrieval ability from secondary memory. When the two groups were averaged, the primary memory capacity was about 3.48 and the average of secondary memory was 2.18. Our results indicated that primary memory capacity was much higher (4.43 items) but that secondary memory retrieval was a little lower (1.98 items). The overall total short-term memory capacity would be very similar in both cases, but the measurement of the two constructs resulted in very different estimates. It is possible that the difference in overall difficulty between the tasks used by Unsworth and Engle (2007b) and our tasks, which were designed for children, could explain the difference in the primary memory capacities. The differences between the difficulty levels of the tasks did not seem to be a valid explanation for the differences in secondary memory retrieval. If overall retrieval was limited perhaps by the retrieval time (Barrouillet, Bernardin, & Camos, 2004), then the different secondary memory retrieval estimates are consistent. For example, regardless of how many items are retrieved from primary memory, if there is a set time limit for retrieval then the items from secondary memory must be retrieved before too much decay had occurred.

Another interesting finding was the quite impressive difference between the primary memory estimates for the child groups and that of the adult group. There was not a large difference in the number of items (almost 3) that the 8-9 year-olds could maintain in primary memory versus the 10-11 year-olds (difference of .09 items). The adult group could maintain close to 1.5 items more in primary memory, making their primary memory estimate close to 4.5 items. Therefore, in looking at differences between the age groups in terms of short-term memory performance, primary memory capacity must develop a great deal during adolescence; whereas, secondary memory retrieval is more consistent throughout the age groups that were included in this study. These results showing age group differences support the findings of Foos et al. (1987), even though very different methodologies were used.

The slopes and correlations of the differing list lengths in the STM and WM tasks for the 8-9 year-old group were surprisingly similar to the adult group, so it seems reasonable to state that children in this age group were able to use primary memory, while it is not as developed as in adults, and they were also able to retrieve items from secondary memory at almost the same level as the adults.

There was another assertion that we tested in the current study regarding the Unsworth and Engle (2006) description of primary memory. This assertion was that one item was always in primary memory during working memory tasks and during short-term memory tasks. This item would always be the final item presented because it did not have any interruption from the processing component of the task before recall. We tested this directly by including a 1-item list length condition in both types of tasks. As can be seen in Tables 1-3, the means for the list length 1 conditions range from .97-1.00 with *SD*s ranging from .02-.07 across the different age groups. This variance indicates that none of the groups had perfect performance for the 1-item conditions. Thus, our data suggest that one item is not always maintained in a 1-item trial without any retrieval interference.

Conceptual Replication of Unsworth and Engle (2006)

To facilitate comparisons between the current results and those reported in Unsworth and Engle (2006), we started with the proportion correct serial position scoring for each of the list length conditions in the short-term memory and working memory tasks. In each of the three age groups, our ANOVA results examining the slopes of the decline in performance for each type of task was similar to Unsworth and Engle (2006). Especially noteworthy were the results of the comparison between the long list length conditions in the 8-9 year-old group. The slopes of the lines were so close for the list lengths 5-7 for the short-term memory task and list lengths 3-5 for the working memory task that the ANOVA failed to produce a significant interaction effect; whereas, the adult group and the Unsworth and Engle (2006) group had a small but significant interaction effect for the same comparison.

The correlation analyses between the list length conditions and fluid intelligence did not fully replicate Unsworth and Engle (2006) in the adult group. In general, the correlations in our young adult group were smaller and some of the predicted correlations with the longer list lengths and fluid intelligence were not significant. There were many similarities between our correlation coefficients and the ones reported by Unsworth and Engle (2006). For instance, our adult group showed higher correlations with intelligence for the longer list length conditions in the short-term memory tasks and in the longer list lengths of the working memory tasks. These short-term memory correlations were reduced substantially when the working memory list length conditions were partialled out. The working memory correlations were reduced somewhat when the short-term memory correlations were partialled out but not as much as in the previous analysis. These findings indicated that longer list lengths in the short-term memory tasks were measuring secondary memory capacity, and by removing the variance associated with the working memory list lengths which also measure secondary memory capacity, the overall level of the correlation should be similar to that between primary memory and intelligence.

There were also differences in the pattern of results for the 8-9 year-old group and the 10-11 year-old group. The 8-9 year-old group did show significant correlations between the longer list lengths in both the short-term and working memory tasks but both sets of correlations were decreased by removing the variance associated with the other task, with the working memory list length correlations showing a greater reduction than the short-term memory list length correlations. This finding may indicate that for this age group, the long short-term memory conditions are a better indicator of secondary memory than the working memory conditions. There was also a reduction in the raw correlations in the working memory task, with the list length 5 condition having the lowest correlation with intelligence than any of the other 4 conditions. The 10-11 year-old group was much more problematic in terms of correlations between the list length conditions and fluid intelligence. Only one of the list length conditions, working memory list length 5 condition, was significantly correlated with the fluid intelligence composite scores. Without significant correlations, the 10-11 year-old group could not replicate any other part of the Unsworth and Engle (2006) findings, which relied heavily on the hypothesized relationship between secondary memory and intelligence and the lack of a relationship between primary memory and intelligence. These findings suggest that 10-11 year-olds may be in a transition period in their development, as their results were quite different from the other two age groups.

The simultaneous and multiple regression analyses for the adult group also did not provide a complete replication of Unsworth and Engle (2006). With the three factors, short-term memory list lengths 1-3, short-term memory list lengths 5-7, and working memory list lengths 3-5, the greatest contributors to variance in fluid intelligence were working memory factor and the shared contribution of the two short-term memory factors. Unsworth and Engle's primary contributor to fluid intelligence was the shared contribution of the working memory factor and the short-term memory long list lengths factor. This primary contributor supported their hypothesis that both of these factors tap retrieval from secondary memory, which is a strong predictor of fluid intelligence. Our results, however, suggested a dual-factor model that predicts fluid intelligence which does not fit into the primary and secondary memory model suggested by Unsworth and Engle (2006). Additionally, when the scope of attention is added as a factor, it contributes more unique variance than the working memory factor. A large portion of shared variance was observed between the scope of attention factor and the working memory factor in the prediction of fluid intelligence. This finding supports Cowan et al.'s (2005) results that showed the scope of attention to be an important contributor to intelligence and that it shared variance with working memory.

One important side note is that there was not a large amount of variance shared between the short-term memory list lengths 1-3, which were intended to measure primary memory, and the scope of attention. These two factors, primary memory and the scope of attention, are theoretically identical but the lack of shared variance suggests that either the two constructs are distinct or that the measurement of one is not valid.

The 8-9 year-old group also did not replicate Unsworth and Engle's (2006) findings in the simultaneous and multiple regression analyses. By far, the strongest contributor of variance to fluid intelligence was the shared variance between the two short-term memory factors in the three factor model. In this group, the three factors predicted a larger amount of variance in fluid intelligence than in the adult group. The other two factors that contributed the most were the unique short-term memory list lengths 4-7 factor and the shared working memory and short-term memory list lengths 1-2 factors. This model does not match what would be predicted if these three factors represent primary and secondary memory. In fact, there should not be any shared variance between the working memory and short-term memory list lengths 1-2 because they are supposed to represent two distinct factors, but yet the shared variance is an important contributor.

In turning to the simultaneous and multiple regression analyses with the scope of attention factor added, the 8-9 year-old group's results one again did not match the adult group or Unsworth and Engle (2006). Instead, the shared variances with the short-term memory list lengths 4-7 factor contributed the most to predicting fluid intelligence. The shared variance between the working memory factor, scope of attention, and the long lists short-term memory factor contributed the greatest amount of variance. Once again, this finding supports Cowan et al. (2005) showing that the scope of attention shares variance with working memory and in this case, the long lists short-term memory factor, and the scope of attention was a predictor of fluid intelligence, but not alone in this model.

The 10-11 year-old group could not add much to our understanding of how primary and secondary memory relate to fluid intelligence. In this age group, the measurements of primary and secondary memory were not even significantly correlated with fluid intelligence, with the single exception of the longest list length condition in the working memory tasks. The disparity of significant correlations was most likely reflective of the fact that the three measures of fluid intelligence did not correlate with each other very strongly. In fact, only one of the three correlations was significant. These measures, although intended for use with children, did not seem to measure the same aspect of fluid intelligence in this age group. This could reflect some type of unintentional sampling bias, in which children with abnormal memory abilities were more likely to volunteer for participation in the study. Neurologically, these children are nearing or have started a pubertal change, which is also known to be the peak of gray matter development, but the white matter will continue to increase throughout adolescence and into young adulthood (Bunge & Wright, 2007; Giedd et al., 1999). These changes in gray matter are followed by widespread cell death during adolescence and the areas with increased gray matter are not well-connected to other areas of the brain through white matter development. These changes in the brain are affecting primarily the frontal lobes, and specifically the areas of the brain known to be important to working memory, and could possibly be upsetting the typical relationship between working memory and intelligence.

In terms of the means for this age group for the important variables, they fell between the youngest age group and the young adult group, as would be expected. In comparing the means on tasks used in this study and in the Cowan et al. (2005) Experiment 1, the 10-11 year old age group in our study had slightly lower scores than their sample, but that difference between the samples was also seen in the comparisons between the adult groups and the 8-9 year-old groups. When we examined the 10-11 year-old group for outliers, the only two that could be identified were close to 2.5 standard deviations from the mean, not exceeding 3 standard deviations and removing these individuals did not dramatically alter the relationship between short-term memory/working memory and fluid intelligence.

Methodological Comparisons

To begin the comparisons, we examined how our study differed from Unsworth and Engle (2006). In many ways, our adult sample's results replicated Unsworth and Engle (2006), but as mentioned previously, there were several outcomes that did not replicate those of Unsworth and Engle (2006). There were many possible methodological differences between the two studies that could explain the differences. The most obvious perhaps is sample size. In our study, we had 53 adult volunteers, but the Unsworth and Engle (2006) sample included 235 adults. One other clear difference between the studies was the tasks selected to measure short-term and working memory. Our study, with a clear focus on developmental differences, utilized less difficult working memory tasks: the counting span and listening span; whereas, Unsworth and Engle (2006) utilized operation span and reading span, which have greater loads on basic arithmetic knowledge and reading ability. Furthermore, in both studies, the word span was utilized as a short-term memory task, but we used the digit span as the other short-term memory task and Unsworth and Engle (2006) utilized letter span. We selected the different short-term memory tasks to share features with our working memory tasks. With both word span and listening span, the items-to-be-recalled were words so we wanted to have the same relationship between digit span and counting span. With the difference of tasks, it is important to note that we did not see ceiling performance for any of our tasks, suggesting that the difficulty was sufficient to allow for enough variability in the study.

There were also differences in the tasks selected to measure fluid intelligence. With our desire to examine young children, we wanted to select measures that were commonly used with those age groups and were easy and engaging enough to keep children involved. For the Unsworth and Engle (2006) participants, only some of the fluid intelligence task trials were selected beforehand to be completed. Our participants completed the entire fluid intelligence tasks for our study (with restrictions in the tasks for ending the task early for a given number of consecutive missed items; WISC-IV tasks). Once again, it was extremely rare for any participants in our study to receive a perfect score on any of the fluid intelligence measures.

Another difference was procedural in nature, Unsworth and Engle's participants had completed a total of 25 different tasks divided between 3 different 1.5-2 hour long sessions, separated by 1-4 weeks each (Kane et al. 2004). These sessions were also partially counterbalanced while our sessions utilized a single task order. Our adult participants completed the entire experiment in a single two hour session. Another possible difference was that the experimenters entered data for the working memory tasks and fluid intelligence tasks, but the participants in Unsworth and Engle (2006) entered their own data for the short-term and working memory tasks, and fluid intelligence tasks. In is not completely evident how these differences might have influenced the relationship between memory performance and fluid intelligence. However, the youngest age group in our study had results that replicated Unsworth and Engle (2006) in many aspects better than the young adult group. This difference could speak to the difference in difficulty levels between the tasks: our tasks designed to be simpler might have been a more similar level of difficulty to the tasks used by Unsworth and Engle (2006) for use by adult participants.

Next we examined the methodological differences between the current study and Cowan et al. (2005). There were some differences in the tasks used: they did not use word span, they did use a third scope of attention task called memory for ignored sounds, and they did not administer the intelligence measures but obtained them from the participants or the participants' schools. They used a fixed order of tasks but they always used two different sessions, each lasting 1-1.5 hours. The sample size was very similar between each of the experiments presented in Cowan et al. (2005) and our study. They used a different method of scoring that was not dependent on the list lengths for the short-term and working memory tasks. We also saw differences in the reliability of our visual array comparison task compared to Cowan et al. (2005). Our visual array comparison task had very low reliability (See Appendix E) and did not correlate well with the running span task, likely due to the lack of reliability. This lack of reliability was likely due to substantially fewer trials in our version of the task (36 trials) compared to Cowan et al.'s (2005; 128 trials).

The results of the multiple regression analyses supported Cowan et al. (2005) more strongly than Unsworth and Engle (2006). The Cowan et al. (2005) Experiment 1 findings demonstrated differences in the prediction of intelligence between the child groups and the adult group. For the adult group from Cowan et al. (2005), the shared variance between the three factors: working memory tasks, digit span, and scope of control, was the largest amount of variance followed by the unique variance from the working memory tasks. This result of shared variance between the different factors being the most important was replicated in our findings. There were slight differences between the adult and child groups as well in Cowan et al. (2005). In their child group, the shared variance between the scope of attention and digit span was the greatest, and the shared variance between the three factors was also an important contributor. The unique variances for each of the three factors contributed about the same amount of variance, with the greatest unique contributor of the three being the digit span. In our child group, we saw that the short-term memory long list lengths contributed a large amount of variance in addition to the shared scope of attention factor with other factors.

Do Children Use Primary and Secondary Memory Like Adults?

Like most areas of psychology, the answer is most likely a combination of yes and no. The children showed similar performance levels to adults in both short-term memory tasks and working memory tasks. The difference between children and adults seemed to be in the relationship between secondary memory and fluid intelligence. The adult group in the current study did not replicate entirely the results of Unsworth and Engle (2006) which were clear in that the elements measuring secondary memory were also the elements that predicted intelligence. In the current study, none of the age groups showed this clear pattern. Instead, with the 8-9 year-old group and the adults, there was evidence that another factor, the scope of attention, contributed to the prediction of intelligence as much or more than the secondary memory factors. Overall, these results call into question the validity of dividing short-term and working memory task performance into primary memory capacity and average retrieval from secondary memory. The model for the 8-9 year-olds did not match the adult model either, suggesting that there are differences in how performance in these tasks relate to intelligence for different age groups.

The Measurement and Analysis of Primary and Secondary Memory

Primary and secondary memory were measured very differently during the 1960s-1980s, compared to the current research. Almost all of the research was done with adult participants and the researchers primarily depended on immediate free recall tasks to measure the two constructs (Watkins, 1974). The goal of that body of work was mostly to determine the structure of short-term memory and to explain the phenomenon of the recency effect (Waugh & Norman, 1965). The goals of some working memory research of more recent times has been to examine the processes involved in working memory task performance and to explain why working memory is related to intelligence (Conway et al., 2002; Cowan, 2001). Unsworth and Engle

(2006) utilized the concepts of primary and secondary memory to better understand possible processes underlying working memory performance. Their methods were in some ways an improvement over the previous methods of measuring primary and secondary memory because these methods allowed for multiple techniques for calculating an individual's primary memory capacity and therefore know how much of the recalled memory came from secondary memory retrieval (Watkins, 1974). This improvement was especially vital to our goal for the current study, which was to examine how primary memory differed between child and adult age groups. De Alwis et al. (2009) made the assumption that all age groups had a capacity of 4 items in primary memory. However, our results indicated that the 8-9 year-olds only had a capacity of 2.9 items.

While the differentiation of primary and secondary memory in a short-term or working memory task might be novel method of analyzing the underlying processes, we were not able to support the findings of Unsworth and Engle (2006) that only secondary memory was predictive of fluid intelligence. We were also unable to show the link between primary memory and the scope of attention, two constructs with very similar definitions, but in our study, they had very little shared variance. In these two discrepancies, we see that the theoretical definitions and assertions do not match the results. The theoretical difficulties related to primary and secondary memory measurement were likely an important reason that research on these constructs declined in the 1980s. Although the Unsworth and Engle (2006) method of measuring primary and secondary memory has been shown to be more reliable than previous methods, these methods were not able to impart a better understanding of the underlying processes involved in working memory nor a better understanding for why working memory task performance is a stronger predictor of intelligence than short-term memory task performance.

Future Directions and Conclusions

The current study examined how primary memory and secondary memory are different between children and adults. However, it seems evident now that the relationships between short-term memory task performance, working memory task performance, and fluid intelligence change with development, and may be more complicated than suggested by Unsworth and Engle (2006). We were able to offer support for Cowan et al. (2005) by showing that the scope of attention is an important factor related to working memory performance and predicting fluid intelligence. More research is needed to examine how children's performance of working memory and short-term memory tasks differs from that of adults.

Another interesting observation in the course of this research was the different methods used by different researchers to examine practically identical data. These different scoring methods not only can obscure the similarities between studies, but they can lead to different conclusions about the processes being studied. It is important for similar scoring techniques to be adopted so that cross-study comparisons can help the field grow instead of dwelling on differences found by different camps of researchers. Children seemed to perform short-term memory tasks and working memory tasks similarly to adults, which the largest difference being the number of items which children can hold actively while performing these tasks.

At the beginning we set out to learn about how working memory "works" and why working memory predicts intelligence. For the 8-9 year-old group, the working memory factor was less important that the long list length factor from the short-term memory factor. However, the working memory factor was more important that either of the short-term memory factors. This finding suggests that children use different processes for working memory than the young adult group. This factor might be as simple as rehearsal processes, which are not generally utilized by the younger age group, to more complicated combinations of processes. The long list length short-term memory factor for the youngest age group likely required more complicated processing to be able to perform similar to the complicated processing used by the young adult group during the working memory tasks. The importance of understanding the scope of attention is increased given the current results. It seemed obvious that the scope of attention tasks were not measuring primary memory capacity, even though the definition would have suggested that the two constructs are the same. Since the scope of attention is an important factor in predicting fluid intelligence for both the 8-9 year-old group and the young adult group, this construct could provide an age-constant means for understanding the relationship between short-term memory and working memory as well as the understanding for why these factors are predictive of fluid intelligence.

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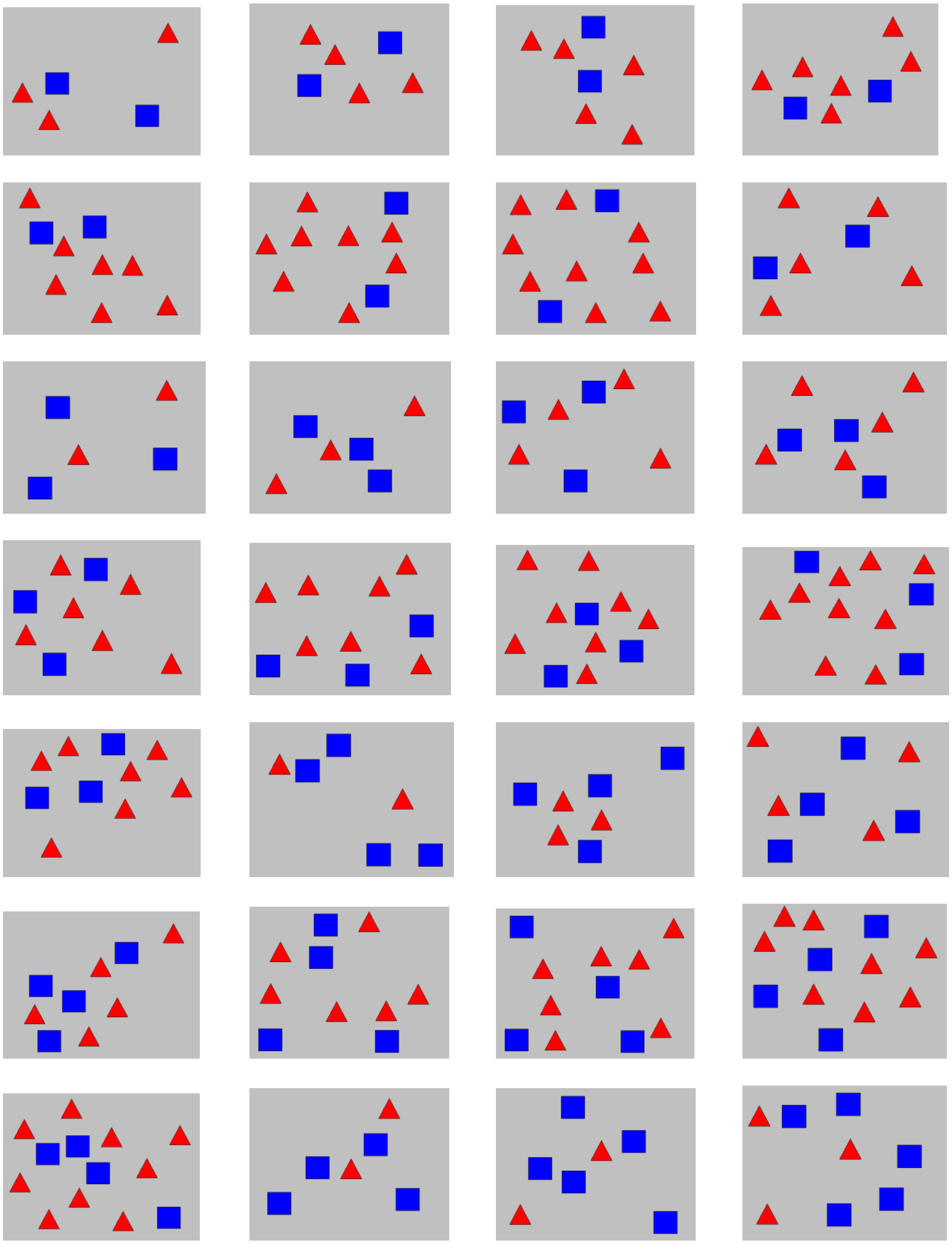
APPENDIX A

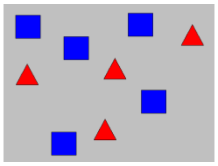
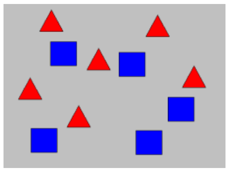
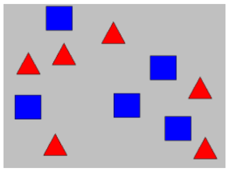
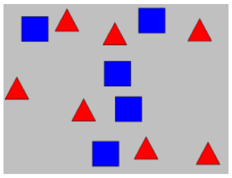
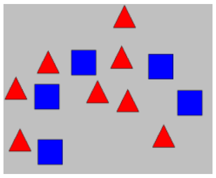
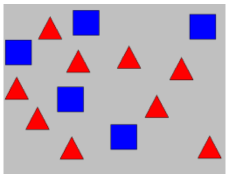
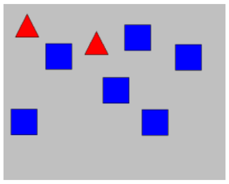
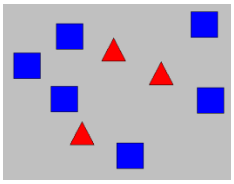
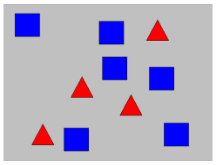
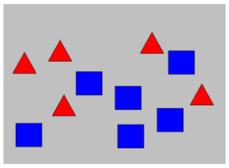
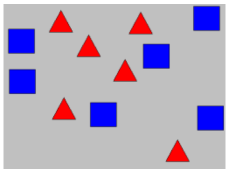
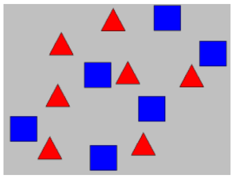
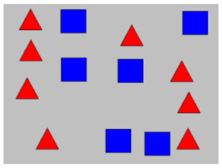
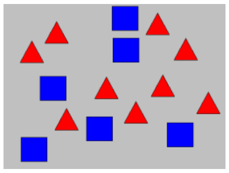
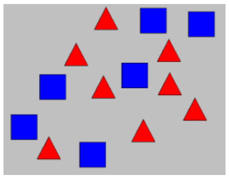
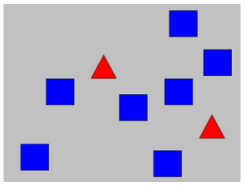
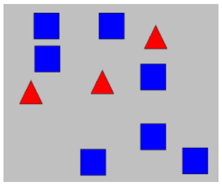
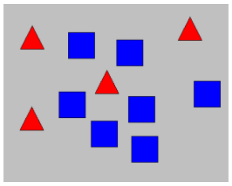
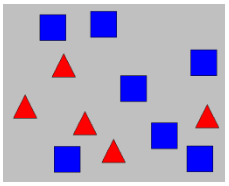
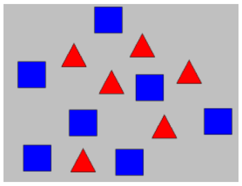
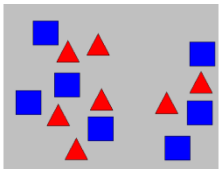
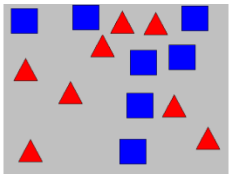
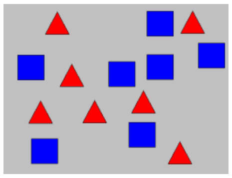
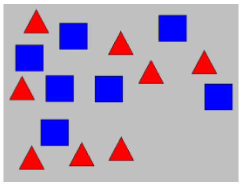
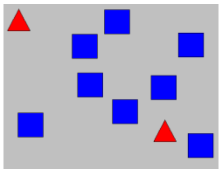
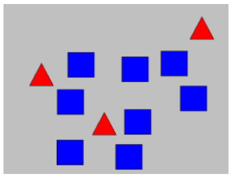
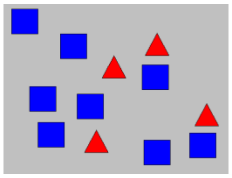
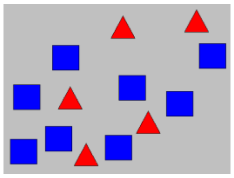
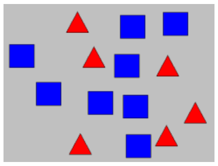
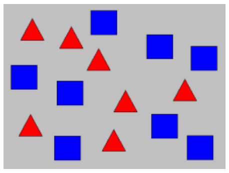
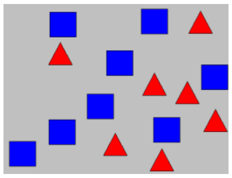
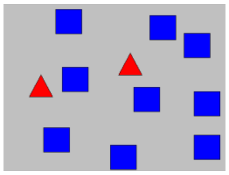
LIST OF WORDS USED IN WORD SPAN TASK

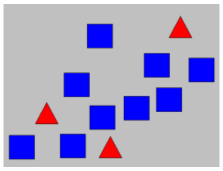
Practice Stimuli	List Length 1	List Length 2	List Length 3	List Length 4	List Length 5	List Length 6	List Length 7
sun	summer	help	smile	step	brush	pocket	road
ticket	year	march	tear	land	ball	heat	woman
line	voice	cold	aunt	arm	window	fight	ground
ring	iron	head	half	dress	dad	car	game
page		picture	face	uncle	drink	guess	answer
book		whisper	park	box	turn	paper	close
coat		church	lunch	place	station	wash	nurse
lady		jump	butter	brother	night	winter	school
			cover	mother	nod	find	dog
			water	egg	call	supper	try
			hold	wood	play	salt	smoke
			coffee	heart	age	back	rest
				people	bag	eye	fruit
				ice	money	room	men
				letter	hall	shop	knee
				look	lie	note	cake
					whole	burn	garden
					square	minute	girl
					sound	walk	music
					bed	juice	ship
						wrong	bridge
						door	home
						touch	body
						nose	saw
							fat
							green
							spot
							finish

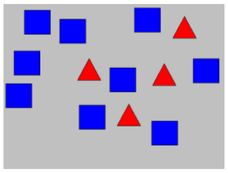
APPENDIX B

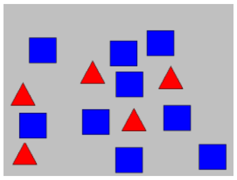
PICTURE STIMULI USED IN THE COUNTING SPAN TASK

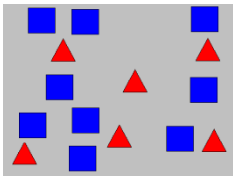


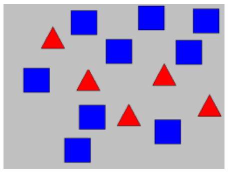











































APPENDIX C

LIST OF SENTENCES USED IN THE LISTENING SPAN TASK

Sentence	T or F	List Length Condition	Percent Accuracy
Always wear your seatbelt in the car.	T	1	0.99
A frog says meow.	F	1	0.98
Cats chase mice.	T	1	0.99
A shape with three sides is a square.	F	1	0.95
A kitten is a baby dog.	F	2	0.99
Camels have humps.	T	2	1.00
Sally is a girl's name.	T	2	0.98
A giraffe has a long neck.	T	2	0.99
Cheetahs run slowly.	F	2	0.98
Bears sleep all summer.	F	2	0.89
Sugar is sweet.	T	2	1.00
A bicycle has four wheels.	F	2	0.83
Rats can read books.	F	3	1.00
Dogs chase cats.	T	3	0.99
A triangle has four corners.	F	3	0.95
A snake is covered with fur.	F	3	1.00
You sleep in a piano.	F	3	0.99
A circle is round.	T	3	0.99
Plants grow from seeds.	T	3	1.00
Ducks wear shoes.	F	3	1.00
A monkey has a long tail.	T	3	0.94
Airplanes fly in the water.	F	3	1.00
Curtains cover a window.	T	3	0.98
Birds eat worms.	T	3	0.98
You wear pants on your arms.	F	4	0.99
A robin is a bird.	T	4	0.99
You can make a snowman in the desert.	F	4	0.98
Some kites look like a diamond.	T	4	0.98
Rain makes things dry.	F	4	0.97
A chicken lays eggs.	T	4	0.98
Leaves change color in the fall.	T	4	0.99
Ants live in the ground.	T	4	0.88
A hat goes on your head.	T	4	1.00
In winter it is very hot.	F	4	0.98
A sheep says moo.	F	4	0.99

We see things with our nose.	F	4	0.99
You wash clothes in the oven.	F	4	1.00
You can boil water in a pot.	T	4	0.99
Trees are made of rock.	F	4	1.00
Some kids ride a bus to school.	T	4	1.00
Mom cooks food in the bed.	F	5	0.99
Elephants are blue.	F	5	0.96
Toads live in a couch.	F	5	1.00
You keep clothes in a dresser.	T	5	0.99
You can smell things with your eyes.	F	5	0.99
Firemen put out fires.	T	5	0.99
Birds flap their wings to fly.	T	5	1.00
Sunlight and water make plants grow.	T	5	0.98
Mittens go on your hands.	T	5	0.99
People can ride on a horse.	T	5	0.99
Dogs have two legs.	F	5	0.95
A cat likes drinking milk.	T	5	0.98
The number after eight is nine.	T	5	0.97
A parrot can fly a plane.	F	5	0.99
Cows eat pudding.	F	5	1.00
Most grass is red.	F	5	0.99
You leave a building through the roof.	F	5	0.98
In the winter, some birds fly south.	T	5	0.94
Some cats sleep in the sun.	T	5	0.83
You eat at a table.	T	5	1.00
Fire is very cold.	F	Practice	1.00
Milk comes from cows.	T	Practice	0.99
A swan has purple feathers.	F	Practice	0.97
You can see stars at night.	T	Practice	1.00
Turtles run quickly.	F	Practice	0.98

APPENDIX D

MEANS AND STANDARD DEVIATIONS FOR ALL OF THE TASKS AND MEASUREMENT TECHNIQUES

	8-9 year olds		10-11 year olds		Young Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
Block Design	28.11	10.79	37.74	10.14	50.66	6.93
Matrix Reasoning	20.17	4.80	24.97	3.38	26.08	3.83
Raven's Matrices	34.81	9.30	39.88	6.54	46.89	6.31
Visual Array Capacity	2.74	1.40	3.14	1.27	4.26	0.89
Run Span Capacity	2.41	0.64	2.58	0.55	3.28	0.64
Digit Span Perfect Recall	3.19	1.04	3.06	1.15	4.94	1.61
Word Span Perfect Recall	2.61	0.99	2.88	0.88	3.92	0.78
Count Span Perfect Recall	1.69	0.75	2.09	0.79	2.64	1.00
Listen Span Perfect Recall	1.06	0.67	1.38	0.78	2.19	1.00
Digit Span Cumul Span	4.37	0.77	4.58	0.67	6.17	0.66
Word Span Cumul Span	3.51	0.66	3.76	0.39	5.08	0.63
Count Span Cumul Span	2.85	0.67	3.21	0.55	3.87	0.55
Listen Span Cumul Span	1.82	0.63	2.34	0.58	3.19	0.79
Digit Span Trad Span	4.72	1.06	5.09	0.93	6.55	0.61
Word Span Trad Span	3.61	0.77	3.97	0.39	5.55	0.85
Count Span Trad Span	3.22	0.96	3.65	0.73	4.32	0.75
Listen Span Trad Span	2.14	0.87	2.59	0.82	3.45	1.01
Digit Span Max Span	3.53	0.91	3.68	0.84	5.55	1.07
Word Span Max Span	2.86	0.80	3.06	0.65	4.11	0.82
Count Span Max Span	1.92	0.65	2.32	0.88	2.94	0.95
Listen Span Max Span	1.39	0.60	1.56	0.61	2.40	0.95
Digit Span Prop Correct	0.66	0.12	0.70	0.10	0.92	0.07
Word Span Prop Correct	0.52	0.14	0.60	0.09	0.80	0.09
Count Span Prop Correct	0.59	0.14	0.67	0.12	0.80	0.11
Listen Span Prop Correct	0.37	0.15	0.54	0.11	0.68	0.17
Digit Span Absolute Score	50.11	15.57	54.71	14.88	89.91	16.39
Word Span Absolute Score	33.67	10.79	37.32	6.38	64.06	14.70
Count Span Absolute Score	24.83	9.14	29.85	7.57	40.13	9.27
Listen Span Absolute Score	11.92	7.41	17.88	6.90	29.34	11.77

The following tables show the correlations between the fluid intelligence tasks, scope of attention tasks, and the various measurements used for each of the short-term memory and working memory tasks for each age group separately.

Correlations between the tasks and various measurements of the short-term memory and working memory tasks for the 8-9 year-old group.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1. Block Design	--																											
2. Matrix Reasoning	0.53	--																										
3. Raven's Matrices	0.64	0.77	--																									
4. Visual Array Capacity	0.13	0.43	0.26	--																								
5. Run Span Capacity	0.21	-0.08	0.26	-0.03	--																							
6. Digit Span Perfect Recall	0.32	0.09	0.21	0.28	0.57	--																						
7. Word Span Perfect Recall	0.22	0.17	0.37	-0.04	0.46	0.21	--																					
8. Count Span Perfect Recall	0.37	0.18	0.21	0.11	0.12	0.26	0.26	--																				
9. Listen Span Perfect Recall	0.55	0.48	0.72	0.27	0.24	0.15	0.29	0.32	--																			
10. Digit Span Cumul Span	0.44	0.31	0.42	0.22	0.55	0.62	0.47	0.39	0.36	--																		
11. Word Span Cumul Span	0.44	0.46	0.48	0.25	0.41	0.39	0.64	0.40	0.47	0.69	--																	
12. Count Span Cumul Span	0.36	0.30	0.35	0.17	0.30	0.33	0.56	0.76	0.45	0.56	0.69	--																
13. Listen Span Cumul Span	0.48	0.37	0.42	0.27	0.41	0.27	0.42	0.34	0.74	0.45	0.65	0.51	--															
14. Digit Span Trad Span	0.36	0.35	0.35	0.22	0.40	0.34	0.41	0.32	0.26	0.86	0.66	0.44	0.38	--														
15. Word Span Trad Span	0.34	0.42	0.43	0.30	0.30	0.35	0.47	0.34	0.43	0.58	0.90	0.62	0.55	0.60	--													
16. Count Span Trad Span	0.34	0.28	0.32	0.17	0.23	0.30	0.42	0.53	0.42	0.47	0.55	0.85	0.43	0.29	0.51	--												
17. Listen Span Trad Span	0.49	0.41	0.41	0.16	0.39	0.22	0.40	0.24	0.57	0.47	0.62	0.46	0.90	0.45	0.56	0.41	--											
18. Digit Span Max Span	0.24	0.11	0.23	0.20	0.50	0.59	0.39	0.29	0.32	0.73	0.44	0.47	0.46	0.42	0.34	0.45	0.41	--										
19. Word Span Max Span	0.35	0.38	0.47	0.12	0.32	0.17	0.69	0.26	0.39	0.48	0.74	0.51	0.49	0.43	0.52	0.27	0.36	0.26	--									
20. Count Span Max Span	0.30	0.12	0.22	0.14	0.24	0.32	0.48	0.65	0.27	0.56	0.52	0.69	0.35	0.46	0.45	0.44	0.33	0.42	0.42	--								
21. Listen Span Max Span	0.02	0.12	0.01	0.20	0.10	0.06	0.07	0.34	0.23	-0.06	0.22	0.25	0.44	-0.05	0.15	0.09	0.33	0.03	0.18	0.16	--							
22. Digit Span Prop Correct	0.49	0.47	0.46	0.22	0.32	0.48	0.44	0.47	0.32	0.91	0.69	0.63	0.37	0.85	0.63	0.50	0.42	0.57	0.46	0.63	-0.08	--						
23. Word Span Prop Correct	0.42	0.49	0.48	0.07	0.29	0.28	0.55	0.40	0.38	0.67	0.85	0.60	0.48	0.71	0.79	0.53	0.55	0.33	0.54	0.42	0.11	0.72	--					
24. Count Span Prop Correct	0.27	0.27	0.28	0.18	0.30	0.36	0.53	0.67	0.38	0.50	0.67	0.95	0.45	0.36	0.58	0.87	0.42	0.45	0.42	0.59	0.20	0.54	0.57	--				
25. Listen Span Prop Correct	0.42	0.34	0.46	0.25	0.49	0.41	0.38	0.51	0.66	0.44	0.58	0.56	0.84	0.37	0.49	0.45	0.74	0.36	0.43	0.33	0.53	0.34	0.51	0.52	--			
26. Digit Span Absolute Score	0.45	0.35	0.43	0.22	0.50	0.56	0.47	0.38	0.38	0.99	0.70	0.55	0.46	0.90	0.58	0.45	0.49	0.70	0.47	0.53	-0.04	0.92	0.69	0.49	0.43	--		
27. Word Span Absolute Score	0.43	0.48	0.48	0.26	0.39	0.40	0.58	0.40	0.48	0.69	0.99	0.66	0.66	0.66	0.90	0.53	0.62	0.45	0.71	0.49	0.27	0.68	0.85	0.64	0.59	0.70	--	
28. Count Span Absolute Score	0.33	0.26	0.29	0.17	0.31	0.33	0.58	0.69	0.44	0.55	0.68	0.98	0.52	0.42	0.62	0.86	0.47	0.48	0.49	0.68	0.22	0.59	0.60	0.95	0.55	0.54	0.66	--
29. Listen Span Absolute Score	0.45	0.36	0.39	0.26	0.41	0.27	0.41	0.35	0.70	0.45	0.64	0.51	0.98	0.37	0.52	0.44	0.91	0.49	0.45	0.35	0.53	0.36	0.48	0.46	0.82	0.47	0.66	0.53

Note: Values greater than .33 are $p < 0.05$ and values greater than .43 are $p < 0.01$.

Correlations between the tasks and various measurements of the short-term memory and working memory tasks for the 10-11 year-old group.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1. Block Design	--																											
2. Matrix Reasoning	0.15	--																										
3. Raven's Matrices	0.30	0.34	--																									
4. Visual Array Capacity	0.15	0.36	-0.17	--																								
5. Run Span Capacity	0.07	-0.10	0.09	0.01	--																							
6. Digit Span Perfect Recall	0.03	-0.10	-0.10	0.05	0.19	--																						
7. Word Span Perfect Recall	-0.09	0.19	0.28	-0.16	0.15	-0.17	--																					
8. Count Span Perfect Recall	-0.16	-0.01	0.05	0.09	0.40	0.16	0.23	--																				
9. Listen Span Perfect Recall	-0.24	-0.01	-0.38	0.13	0.15	0.24	-0.24	0.04	--																			
10. Digit Span Cumul Span	0.03	-0.04	-0.17	0.23	0.43	0.41	0.03	0.33	0.19	--																		
11. Word Span Cumul Span	-0.17	0.23	0.42	-0.05	0.34	0.08	0.65	0.36	-0.04	0.14	--																	
12. Count Span Cumul Span	-0.23	-0.05	-0.05	0.14	0.13	0.18	0.30	0.72	0.00	0.30	0.25	--																
13. Listen Span Cumul Span	-0.23	-0.13	-0.19	0.05	0.20	0.43	-0.23	0.23	0.74	0.23	0.08	0.23	--															
14. Digit Span Trad Span	0.03	-0.18	-0.12	0.12	0.51	0.19	0.16	0.40	0.16	0.85	0.12	0.39	0.24	--														
15. Word Span Trad Span	-0.18	0.02	0.2	-0.06	0.26	0.41	-0.01	0.30	0.14	0.16	0.61	0.17	0.35	0.01	--													
16. Count Span Trad Span	-0.01	0.17	-0.21	0.28	-0.03	0.10	-0.02	0.26	-0.02	0.22	-0.03	0.62	0.11	0.14	0.18	--												
17. Listen Span Trad Span	-0.11	-0.14	0.04	-0.14	0.17	0.28	-0.07	0.24	0.40	0.10	0.09	0.27	0.82	0.17	0.25	0.10	--											
18. Digit Span Max Span	-0.15	0.29	0.02	0.31	0.08	0.24	0.11	0.04	-0.04	0.56	0.18	0.02	-0.20	0.23	0.06	0.10	-0.33	--										
19. Word Span Max Span	-0.21	0.26	0.40	-0.18	0.06	-0.09	0.76	0.05	-0.23	-0.10	0.69	0.05	-0.11	-0.01	0.25	-0.15	0.05	0.15	--									
20. Count Span Max Span	-0.09	0.01	-0.07	0.18	-0.06	0.19	0.01	0.7	0.08	0.16	0.10	0.76	0.31	0.26	0.12	0.37	0.28	-0.10	-0.09	--								
21. Listen Span Max Span	-0.18	-0.07	-0.35	-0.07	0.07	0.30	-0.16	-0.11	0.75	0.13	0.06	0.11	0.56	0.07	0.20	0.18	0.23	-0.11	-0.16	0.10	--							
22. Digit Span Prop Correct	0.01	-0.15	-0.18	0.13	0.38	0.22	0.23	0.43	0.08	0.87	0.25	0.48	0.13	0.85	0.11	0.27	0.05	0.39	-0.06	0.24	0.08	--						
23. Word Span Prop Correct	-0.14	0.18	0.26	0.00	0.29	0.03	0.41	0.33	0.14	0.30	0.69	0.37	0.27	0.37	0.35	0.10	0.20	0.20	0.38	0.26	0.16	0.45	--					
24. Count Span Prop Correct	-0.10	0.05	0.05	0.14	0.01	0.32	0.29	0.58	-0.05	0.30	0.15	0.90	0.17	0.36	0.10	0.52	0.20	0.03	0.06	0.71	0.11	0.40	0.23	--				
25. Listen Span Prop Correct	-0.12	0.10	0.11	-0.04	0.06	0.39	-0.07	0.18	0.38	-0.03	0.19	0.21	0.77	-0.01	0.36	0.16	0.80	-0.24	0.02	0.27	0.24	-0.05	0.29	0.17	--			
26. Digit Span Absolute Score	0.02	-0.04	-0.16	0.21	0.43	0.28	0.08	0.34	0.16	0.99	0.15	0.31	0.18	0.88	0.12	0.21	0.06	0.55	-0.07	0.17	0.10	0.89	0.34	0.29	-0.08	--		
27. Word Span Absolute Score	-0.21	0.21	0.40	-0.04	0.29	0.11	0.50	0.32	0.01	0.13	0.98	0.20	0.13	0.08	0.69	-0.04	0.10	0.17	0.62	0.11	0.12	0.21	0.69	0.29	0.22	0.14	--	
28. Count Span Absolute Score	-0.17	-0.05	-0.06	0.15	0.05	0.17	0.30	0.57	-0.03	0.29	0.19	0.97	0.22	0.38	0.11	0.68	0.26	0.04	0.06	0.69	0.14	0.46	0.33	0.90	0.21	0.31	0.14	--
29. Listen Span Absolute Score	-0.24	-0.14	-0.16	-0.06	0.19	0.41	-0.23	0.21	0.61	0.20	0.07	0.22	0.96	0.21	0.34	0.15	0.83	-0.18	-0.12	0.29	0.49	0.13	0.29	0.15	0.81	0.16	0.12	0.22

Note: Values greater than .34 are $p < 0.05$ and values greater than .43 are $p < 0.01$.

Correlations between the tasks and various measurements of the short-term memory and working memory tasks for the adult group.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1. Block Design	--																											
2. Matrix Reasoning	0.38	--																										
3. Raven's Matrices	0.65	0.67	--																									
4. Visual Array Capacity	0.29	0.29	0.34	--																								
5. Run Span Capacity	0.32	0.04	0.20	0.08	--																							
6. Digit Span Perfect Recall	0.23	0.01	0.12	0.01	0.58	--																						
7. Word Span Perfect Recall	0.10	0.21	0.34	0.08	0.45	0.44	--																					
8. Count Span Perfect Recall	0.20	0.21	0.11	0.08	0.02	0.12	0.06	--																				
9. Listen Span Perfect Recall	0.23	0.00	0.15	0.03	0.19	0.38	0.07	0.15	--																			
10. Digit Span Cumul Span	0.25	0.01	0.07	0.14	0.60	0.71	0.35	0.10	0.19	--																		
11. Word Span Cumul Span	0.29	0.15	0.41	0.13	0.54	0.58	0.58	0.14	0.34	0.62	--																	
12. Count Span Cumul Span	0.33	0.35	0.37	0.19	0.33	0.46	0.19	0.49	0.37	0.45	0.37	--																
13. Listen Span Cumul Span	0.11	0.23	0.18	0.11	0.18	0.34	0.02	0.24	0.73	0.30	0.39	0.57	--															
14. Digit Span Trad Span	0.37	0.16	0.23	0.20	0.37	0.37	0.29	0.14	0.08	0.81	0.54	0.33	0.19	--														
15. Word Span Trad Span	0.21	0.05	0.26	0.19	0.34	0.41	0.36	0.19	0.33	0.46	0.83	0.20	0.31	0.42	--													
16. Count Span Trad Span	0.24	0.18	0.30	0.11	0.31	0.51	0.21	0.18	0.38	0.45	0.36	0.82	0.51	0.28	0.17	--												
17. Listen Span Trad Span	0.01	0.26	0.19	0.11	0.20	0.31	0.09	0.14	0.56	0.28	0.42	0.54	0.90	0.15	0.27	0.49	--											
18. Digit Span Max Span	0.22	0.01	0.04	0.10	0.49	0.69	0.28	0.06	0.23	0.86	0.48	0.36	0.26	0.63	0.39	0.38	0.23	--										
19. Word Span Max Span	0.18	0.07	0.35	-0.02	0.51	0.60	0.61	0.10	0.25	0.49	0.8	0.32	0.25	0.37	0.57	0.34	0.26	0.50	--									
20. Count Span Max Span	0.44	0.30	0.45	0.03	0.21	0.34	0.12	0.34	0.30	0.38	0.36	0.64	0.39	0.32	0.23	0.43	0.37	0.39	0.38	--								
21. Listen Span Max Span	0.25	0.1	0.19	0.03	0.20	0.33	0.04	0.21	0.77	0.30	0.29	0.54	0.82	0.18	0.25	0.49	0.61	0.24	0.19	0.39	--							
22. Digit Span Prop Correct	0.17	-0.06	0.02	0.21	0.56	0.62	0.31	0.09	0.17	0.90	0.54	0.37	0.21	0.70	0.44	0.34	0.20	0.80	0.41	0.28	0.27	--						
23. Word Span Prop Correct	0.18	0.12	0.30	0.12	0.50	0.57	0.51	0.07	0.49	0.68	0.83	0.40	0.56	0.58	0.71	0.40	0.56	0.60	0.68	0.38	0.50	0.63	--					
24. Count Span Prop Correct	0.32	0.29	0.33	0.24	0.36	0.45	0.10	0.40	0.37	0.43	0.32	0.95	0.56	0.29	0.16	0.82	0.55	0.36	0.29	0.62	0.52	0.37	0.38	--				
25. Listen Span Prop Correct	0.25	0.33	0.34	0.19	0.26	0.38	0.13	0.24	0.61	0.31	0.41	0.64	0.90	0.21	0.24	0.59	0.84	0.24	0.27	0.39	0.69	0.21	0.49	0.65	--			
26. Digit Span Absolute Score	0.25	0.02	0.09	0.16	0.60	0.69	0.35	0.10	0.22	0.97	0.62	0.41	0.27	0.81	0.48	0.42	0.25	0.89	0.52	0.37	0.24	0.90	0.67	0.41	0.28	--		
27. Word Span Absolute Score	0.29	0.13	0.40	0.14	0.51	0.56	0.53	0.14	0.36	0.61	1.00	0.37	0.41	0.54	0.84	0.36	0.43	0.48	0.79	0.36	0.30	0.53	0.83	0.33	0.41	0.61	--	
28. Count Span Absolute Score	0.34	0.30	0.38	0.22	0.36	0.49	0.19	0.36	0.40	0.48	0.41	0.98	0.57	0.35	0.23	0.86	0.56	0.38	0.36	0.65	0.54	0.41	0.44	0.96	0.65	0.46	0.42	--
29. Listen Span Absolute Score	0.15	0.24	0.21	0.13	0.21	0.35	0.02	0.21	0.73	0.31	0.42	0.55	0.99	0.20	0.34	0.50	0.90	0.26	0.25	0.39	0.80	0.21	0.58	0.54	0.89	0.29	0.44	0.56

Note: Values greater than .27 are $p < 0.05$ and values greater than .35 are $p < 0.01$.

APPENDIX E

RELIABILITY SCORES

	STM Tasks		WM Tasks		Scope of Attention Tasks	
	Digit Span	Word Span	Count Span	Listen Span	Run Span	VisArray
Adults	0.72	0.77	0.69	0.86	0.87	0.33
8-9 year olds	0.80	0.87	0.78	0.83	0.92	0.32
10-11 year olds	0.75	0.68	0.64	0.62	0.89	-0.05

These reliability scores were calculated by randomly assigning a single trial from each list length to one of four groups. For the memory tasks, then the proportion-correct for that trial was averaged with the other trials assigned to that group. Then a Cronbach's α was calculated for the task by comparing the four groups. For the Running Span Task, the number of correctly recalled digits for a trial was averaged with the other trials assigned to the group, and multiple trials from each list length were included in each of the four groups. Then Cronbach's α was calculated for that task. For the Visual Array Comparison Task, the accuracy of a single trial was averaged with other trials included in the same group. Then Cronbach's α was calculated for that task.

Since the measures used for fluid intelligence are standard measures that have been normed, we obtained the reliability scores for these measures from separate sources.

Task	Reliability	Method
Block Design (WISC-IV)[a]	0.86	split-half correlation
Matrix Reasoning (WISC-IV)[a]	0.89	split-half correlation
Raven's Standard Matrices	0.83	test-retest correlation

Note: [a] indicates source was Williams, Weiss, Rolfhus (2003); the other source was Williams and McCord (2006)

There were concerns about the reliability of the visual array comparison task, so we examined how removing the visual array task from the scope factor in the regression analyses would affect the results. The tables showing the simultaneous and multiple regression analysis (when run for the original analyses) for with the scope composite factor and the running span only factor side-by-side.

All Age Groups					
Variable	*B*	*t*	*sr* ²	*R* ²	*F*
Age	0.174	1.73	0.01		
STM LL1-2	-0.023	-0.32	0.00		
STM LL 5-7	0.282	2.28	0.02		
WM LL 2-5	0.360	3.71	0.06		
Run Span	-0.017	-0.19	0	0.51	24.32**

Variable	*B*	*t*	*sr* ²	*R* ²	*F*
Age	0.141	1.43	0.01		
STM LL1-2	-0.029	-0.44	0.00		
STM LL 5-7	0.204	1.73	0.01		
WM LL 2-5	0.300	3.10**	0.04		
Scope	0.215	2.50*	0.02	0.53	26.84**

Adults					
Variable	*B*	*t*	*sr* ²	*R* ²	*F*
STM LL1-3	-0.005	-0.03	0.00		
STM LL 5-7	-0.064	-0.37	0.00		
WM LL 3-5	0.387	2.63*	0.12		
Run Span	0.133	0.80	0.01	0.173	2.51^

Variable	*B*	*t*	*sr* ²	*R* ²	*F*
STM LL1-3	0.059	0.45	0.00		
STM LL 5-7	-0.136	-0.89	0.01		
WM LL 3-5	0.320	2.25*	0.08		
Scope	0.354	2.44*	0.09	0.254	4.09**

Adults		
Variables with Run Span	*R* ²	*F*
STM 1-3, STM 5-7, WM 3-5, Scope	0.173	2.51^
STM 1-3, WM 3-5, Scope	0.170	3.36*
STM 1-3, STM 5-7, Scope	0.053	0.92
STM 5-7, WM 3-5, Scope	0.173	3.41*
STM 1-3, STM 5-7, WM 3-5	0.162	3.15*
STM 1-3, Scope	0.050	1.30
WM 3-5, Scope	0.170	5.13**
STM 5-7, Scope	0.053	1.39
STM 1-3, WM 3-5	0.175	5.29**
STM 1-3, STM 5-7	0.035	0.92
WM 3-5, STM 5-7	0.162	4.82*
Scope	0.048	2.60
STM 1-3	0.009	0.45
STM 5-7	0.033	1.73
WM 3-5	0.161	9.82**

Variables with Scope	*R* ²	*F*
STM 1-3, STM 5-7, WM 3-5, Scope	0.254	4.09**
STM 1-3, WM 3-5, Scope	0.242	5.21**
STM 1-3, STM 5-7, Scope	0.176	3.48*
STM 5-7, WM 3-5, Scope	0.251	5.48**
STM 1-3, STM 5-7, WM 3-5	0.162	3.15*
STM 1-3, Scope	0.175	5.29**
WM 3-5, Scope	0.241	7.93**
STM 5-7, Scope	0.167	5.01*
STM 1-3, WM 3-5	0.175	5.29**
STM 1-3, STM 5-7	0.035	0.92
WM 3-5, STM 5-7	0.162	4.82*
Scope	0.167	10.21**
STM 1-3	0.009	0.45
STM 5-7	0.033	1.73
WM 3-5	0.161	9.82**

3rd grade					
Variables	*B*	*t*	*sr* ²	*R* ²	*F*
STM 1-2	0.03	0.02	0.00		
STM 4-7	0.42	2.27*	0.11		
WM 2-4	0.28	1.45	0.04		
Run Span	-0.12	-0.65	0.01	0.348	4.15**

Variables	*B*	*t*	*sr* ²	*R* ²	*F*
STM 1-2	-0.07	-0.49	0.00		
STM 4-7	0.40	2.21*	0.10		
WM 2-4	0.18	0.95	0.02		
Scope	0.17	1.08	0.02	0.363	4.42**

3rd Grade						
Variables with Run Span	R^2	F		Variables with Scope	R^2	F
STM 1-2, STM 4-7, WM 2-4, Scope	0.35	4.15**		STM 1-2, STM 4-7, WM 2-4, Scope	0.36	4.42**
STM 1-2, WM 2-4, Scope	0.24	3.37*		STM 1-2, WM 2-4, Scope	0.26	3.81*
STM 1-2, STM 4-7, Scope	0.30	4.66**		STM 1-2, STM 4-7, Scope	0.35	5.61**
STM 4-7, WM 2-4, Scope	0.35	5.70**		STM 4-7, WM 2-4, Scope	0.36	5.96**
STM 1-2, STM 4-7, WM 2-4	0.34	5.48**		STM 1-2, STM 4-7, WM 2-4	0.34	5.48**
STM 1-2, Scope	0.02	0.38		STM 1-2, Scope	0.12	2.30
WM 2-4, Scope	0.24	5.21**		WM 2-4, Scope	0.26	5.77**
STM 4-7, Scope	0.30	7.21**		STM 4-7, Scope	0.34	8.57**
STM 1-2, WM 2-4	0.24	5.06**		STM 1-2, WM 2-4	0.24	5.06**
STM 1-2, STM 4-7	0.30	7.18**		STM 1-2, STM 4-7	0.30	7.18**
WM 2-4, STM 4-7	0.34	8.39**		WM 2-4, STM 4-7	0.34	8.39**
Scope	0.02	0.79		Scope	0.12	4.75**
STM 1-2	0.01	0.24		STM 1-2	0.01	0.24
STM 4-7	0.30	14.77**		STM 4-7	0.30	14.77**
WM 2-4	0.23	10.33**		WM 2-4	0.23	10.33**

5th Grade												
Variables	B	t	sr^2	R^2	F		Variables	B	t	sr^2	R^2	F
STM 1-3	0.36	1.57	0.08				STM 1-3	0.36	1.76	0.09		
STM 5-7	-0.16	-0.49	0.01				STM 5-7	-0.16	-0.83	0.02		
WM 2-5	-0.20	-0.85	0.02				WM 2-5	-0.20	-0.99	0.03		
Run Span	0.22	-0.03	0.00	0.085	0.68		Scope	0.22	1.22	0.04	0.129	1.08

Taken as a whole, removing the visual array comparison task from the scope composite resulted in less variance explained in each model and the factor explaining less variance in fluid intelligence. For the adult group, the simultaneous regression analysis went from being significant at $p < 0.01$ to marginal significance, $p = 0.054$. The difference between the regression analyses for the 8-9 year-old group was not as large, in fact the variance accounted for by the models was only decreased by 1.3%. While the visual array comparison task did not have high reliability, it obviously contributed to the model in an important way. Cowan et al. (2005) also used the visual array comparison task but their version had many more trials (128 vs. 36 in ours) and found high reliability for this measure in all of their age groups.

VITA

Sharon Diane Eaves was born on February 17, 1982, in Euless, Texas, to her parents Charles R. Brown and Shirley A. Brown. She grew up in Texas with her family and attended public schools in Saginaw, Texas, throughout her primary and secondary education. After graduating high school in May 2000 with several honors and ranked 10th in her class, Sharon attended Harding University in Searcy, Arkansas, from 2000-2001 school year and then Tarrant County College from 2001-2002. She transferred the following school year to the University of Texas at Arlington, where Sharon completed her Bachelor of Arts degree in psychology in May 2004, at the top of her graduating class. She then moved to Louisiana to pursue her graduate training in cognitive developmental psychology at Louisiana State University in June 2004. She completed the requirements to earn her Master of Arts degree in psychology in May 2006. Sharon continued at Louisiana State University completing her doctoral training. She completed the requirements to earn her doctorate in the Fall of 2010. She now works at Shawnee State University in Portsmouth, Ohio, as a Senior Instructor of Psychology in the Social Sciences Department.