Recollection, Familiarity, and Working Memory Contributions to Math and Reading Achievement at Ages 6 and 9

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(ABSTRACT)

Academic achievement involves complex processes that are not fully understood. That being said, the connection between working memory and academic achievement is well developed and emphasized in the literature. Considering the complex nature of academic achievement, other processes are likely involved. The current study examined the contributions of recollection, familiarity, working memory, and verbal IQ longitudinally in children at ages 6 and then 9. Recollection, but not familiarity, contributed to measures of both reading and math at age 6, but not 9. Path models suggested that the direct and indirect effects of working and episodic memory to academic achievement change from age 6 to 9. Furthermore, this study examined the contributions of the neural correlates of recollection and working memory to measures of academic achievement at ages 6 and 9. The neural correlates of working memory and recollection did not contribute to academic achievement, but additional research is needed to draw concrete conclusions. Overall, the results suggest that episodic memory should be considered in addition to working memory when examining academic achievement.

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(GENERAL AUDIENCE ABSTRACT)

Academic achievement incorporates many different abilities. I examined how different memory systems impact math and reading achievement at ages 6 and 9 years. I specifically examined working memory, recollection, and familiarity. Working memory involves information that is currently within one's awareness. Recollection is a vivid re-experiencing of an event or events. Familiarity is a general sense that something has been seen or heard previously. The results suggest that working memory and recollection, but not familiarity, primarily impact math and reading achievement. Furthermore, different patterns emerged for the relation between memory and math achievement when compared to reading achievement, but were dependent on the child's age. The results suggest that older children rely on different memory systems for math when compared to reading, while younger children use the same memory systems for math and reading. We further examined the neural (brain) regions related to memory and academic achievement. Additional research is needed to interpret and expand on the neural results found. Overall, the results provide information on how children learn and develop math and reading skills.

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Introduction

Recollection, Familiarity, and Working Memory Contributions to Math and Reading Achievement at Ages 6 and 9

Memory is a multifaceted construct that involves many cognitive abilities and that itself may be broken down into multiple components. These memory components or systems tend to be divided into a hierarchy, beginning with a broad dichotomy (e.g., implicit vs. explicit memory) and then extending into more specific forms of memory (e.g., episodic memory). Implicit memory is a non-declarative form of memory, meaning the conscious recollection is not necessary for the memory to occur (Tulving, 1972). In contrast, explicit memory is declarative and requires conscious recollection during retrieval of a memory. Considering the complex nature of memory, it is not surprising that memory interacts with other cognitive abilities (e.g., executive functions; Baudic, Dalla Barba, Thibaudet, Smagghe, Remy, & Traykov, 2006).

Working memory (WM), or information that you hold online for manipulation and use, is typically viewed alone or as a composite within the broader construct of executive function (i.e., higher order cognitive construct; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). WM is often associated with forms of explicit memory, or more specifically episodic memory (EM), in terms of strategy implementation (Baddeley, 2000; Nyberg et al., 2003). In regard to academic achievement, WM has been a central focus. Several studies have examined the contribution of WM and WM systems on academic success (e.g., Bull, Epsy, & Wiebe, 2008; Nation, Adams, Bowyer-Crane, & Snowling, 1999; Passolunghi, Caviola, De Angostini, Perin, & Mammarella, 2016). Considering the relation between WM and EM, it is likely that EM contributes to academic achievement. However, EM has been rarely examined, especially in the mathematical academic achievement literature.

The intention of this study is to better understand the contributions of components of EM to multiple measures of academic achievement, while controlling for WM and IQ at age 6 and then 9. First, I focus on the constructs of WM and EM, outlining the development and neural correlates of each. Second, I discuss the relation between WM and academic achievement. Third, I will discuss how EM might be related and the possibility of developmental shifts in terms of contributions. Fourth, I outline possible neural overlap between WM, EM, and academic achievement. Finally, I provide an overview of EEG coherence and power literature and provide justifications for possible shifts in the development of the EEG from in 6 to 9-year olds.

1. Working Memory

Baddeley and Hitch originally proposed the construct of WM in 1974. They suggested that WM allows for manipulation and maintenance of information that exists within awareness. The model also posited that WM is limited in storage, meaning that the information that you are able to manipulate at any given time is limited. Within their model, WM was broken down into multiple components. These components were each proposed to handle different modes or processes of information; they included the phonological loop (auditory), visuospatial sketchpad (visual), and central executive (control center). Baddeley (2000) later revised the classic model to include the episodic buffer. The episodic buffer operates across modalities allowing for cross-communication between phonological and visual systems, as well as short term binding of contextual and item information. These systems together allow for complex processes, such as strategy implementation during memory encoding (Baddeley, 2000; Nyberg et al., 2003). Considering the interplay among the systems, I focus on the overarching construct of WM in this study, examining the individual components briefly when discussing developmental differences in WM. The following sections review the development and neural correlates of WM.

1.1 Development of Working Memory

WM performance improves rapidly across early childhood with the initial verbal and visuospatial components in place by age 4 (Alloway, Gathercole, & Pickering, 2006). WM continues to develop throughout middle and late childhood, and has been argued to further develop during adolescence (Isbell, Fukuda, Neville, & Vogel, 2015). The developmental trajectory of maintenance components of WM appears to be linear (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Gathercole, Pickering, Ambridge, & Wearing, 2004), with gradual increases in ability, through increased retention of information, observed with age. These increases in WM capacity have been associated with growth in other cognitive abilities, such as EM (for review see Unsworth & Engle, 2007). Additionally, many of the observed performance increases observed in WM have been attributed to prefrontal cortex maturation (PFC; Luciana & Nelson, 1998; Tamnes et al., 2013).

There is evidence to suggest that individual WM systems also show linear patterns, while developing at different rates. For example, children under the age of 8 do not appear to utilize their phonological loop for effective rehearsal (Halliday, Hitch, Lennon, & Pettipher, 1990; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010). The later development of rehearsal techniques around age 8 may give rise to the recoding of information from the visuospatial sketchpad to the phonological loop (Ford & Silber, 1994; Hitch, Woodin, & Baker, 1989; Palmer, 2000). Recoding information across WM components allows children to develop more complex encoding strategies. Although I focused on an overall measure of WM, it is important to consider how the functioning of WM may differ between 6- and 9-year-old children. Considering the literature, one would assume that a 9 year old would engage in more complex encoding strategies as a result of changes to the structure of WM.

1.2 Neural Correlates of Working Memory

Literature supporting the importance of the prefrontal cortex (PFC) in WM processes is well developed. Frontal regions, specifically the PFC, are typically active during WM tasks in adults (Smith & Jonides, 1999) and children (Bell & Wolfe, 2007; Luciana & Nelson, 1998; Wolfe & Bell, 2004). Additionally, PFC lesions lead to WM deficits (Barbey, Koenigs & Grafman, 2013). The PFC is believed to be responsible maintenance of relevant information within WM (for review see Ku, Bodner, & Zhou, 2015; Miller & Cohen, 2001). Such maintenance mechanisms are believed to aid in long-term retention, or long-term memory (Petrides, 2000). Recall that WM performance continues to display improvements throughout childhood. These improvements coincide with PFC maturation (Diamond, 2000; Huttenlocher, 1979). In fact, the PFC matures throughout childhood and adolescence (Huttenlocher, 1979). Additionally, the PFC is associated with increased activation as a result of age, in 8-24 year old (Ofen et al., 2007), and increased gray matter in 4-20 year old participants (Giedd et al., 1999). To elaborate, Geidd and colleagues conducted a longitudinal MRI study examining gray and white matter maturation associated with age. Relevant for PFC development, they found increases in frontal gray matter, peaking at age 12. This focused on frontal regions when examining WM due to the expansive literature supporting the recruitment of such regions in WM tasks, and the developments observed throughout childhood.

2. Episodic Memory

Episodic memory (EM) is an explicit form of memory that includes contextual (temporal, spatial, etc.) and item information (Tulving, 1972). EM operates based on two primary functions, encoding and retrieval. Storing episodic events in a way that may be used by cognitive systems is referred to as encoding, while the process of reactivating the previously encoded episode is referred to as retrieval (Tulving, 1972). EM encoding and retrieval results in detailed bound (context and item) memory episodes. Additionally, the dual process model of EM recognition focuses on the processes of recollection and familiarity. Recollection allows for vivid re-experience of an item and its context during retrieval, whereas familiarity provides a general sense of knowing that an event has occurred (Ghetti & Lee, 2013; Yonelinas, 2002). Recollection and familiarity are dissociable in both neuroimaging (Diana, Yonelinas, & Ranganath, 2007) and behavioral (Yonelinas, 1999) literature. I focused on the general construct of EM, as well as the specific components of recollection and familiarity, with specific interest being placed on recollection. The following sections review the development and neural correlates of EM.

2.1. Development of Episodic Memory

During middle to late childhood the correlation between performance on WM and EM tasks strengthens (Schneider & Weinert, 1995) and the associations are readily seen in the laboratory (e.g., Blankenship & Bell, 2015). Schneider and Weinert interpreted the strengthening of the correlation between WM and EM to be a result of increased strategy use seen with age. The improved use of strategies or mnemonic techniques may be related to improvement in binding processes (Raj & Bell, 2010). This also might explain why semantic (i.e., knowledge-based) forms of explicit memory stabilize early in development (~6 years), whereas EM, specifically recollection, continues to develop throughout adolescence. To elaborate, recollection continues to develop throughout middle childhood and into adolescence (Ghetti & Angelini, 2008). Familiarity, however, shows fewer developments and actually appears to stabilize in childhood, even as young as 8 years of age (Ghetti & Angelini, 2008). This research further suggests that recollection and familiarity are in fact dissociable processes, and that they display different developmental trajectories.

Recollection and familiarity are often assessed in children using recognition paradigms (Ghetti & Angelini, 2008; Raj & Bell, 2010). The tasks used vary from study to study, but the underlying principles are the same. Familiarity is less effortful and thus should exhibit a shorter reaction time. Furthermore, familiarity occurs in the absence of binding, so if any associations are made, then the task is assumed to elicit recollection. In this study, I examined both recollection and familiarity in 6 and 9 year old children using a recognition paradigm.

2.2. Neural Correlates of Episodic Memory

Both the medial temporal lobe (MTL) and the PFC are active during encoding and retrieval of EMs (Cabeza, Dolcos, Graham, & Nyberg, 2002; Konishi, Wheeler, Donaldson, & Buckner, 2000; Takahashi, Ohki, & Kim, 2007). The hippocampus, which is located within the MTL, is believed to operate as a temporary storage base for EMs (Graham & Hodges, 1997). In addition to operating as a store, the hippocampus is responsible for long-term binding (Davachi, 2006); binding allows for connections to be made between contextual and item information. To elaborate, the hippocampus allows for short-term binded representations from WM, associated with PFC functioning, to be consolidated (Newman & Grace, 1999), thus supporting the cross communication between PFC and MTL regions. The PFC is believed to contribute to EM performance by providing short-term binded representations through WM, therefore supporting mnemonic strategies and organization in adults (Badre & Wagner, 2007; Nyberg et al., 2003) and children (Luciana & Nelson, 1998).

Developments of the PFC cortex were outlined in the WM section. Relatively less is known about hippocampal development. Age-related improvements in EM are often explained through PFC maturation (for review see Kagan & Baird, 2004). Although PFC maturation most definitely contributes to improvements observed in middle childhood EM ability, it is likely that hippocampal maturation also contributes. Ghetti and Bunge (2012) suggested that changes in hippocampal volume might provide insight into how hippocampal maturation influences EM performance. They demonstrated that anterior hippocampal volume decreases and posterior volume increases throughout middle childhood. In adults, less volume in anterior hippocampi and more volume in posterior hippocampi are associated with EM performance (Maguire et al., 2000).

The PFC and MTL display connectivity, meaning there are neuronal connections between the areas. This functional connectivity is associated with EM performance in adults (Grady, McIntosh, & Craik, 2003) and children (Blankenship & Bell, 2015). However, little is known about how the functional connectivity associated with EM changes throughout middle childhood. Frontotemporal connectivity has been suggested to strengthen throughout childhood and adolescence (Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008). However, although functional connectivity has been examined in children (e.g. Sole-Padulles et al., 2016), to my knowledge, frontal and temporal regions have not been examined in terms of maturation in connectivity from ages 6 to 9. I therefore focused on frontotemporal coherence, as well as frontal and temporal power activation in relation to EM (Rajan & Bell, 2015).

3. Academic Achievement

Childhood academic performance is affected by a number of variables. Basic understanding of numbers (e.g., number recognition) and letters (e.g., phonemic awareness) are necessary to build more complex mathematical and reading abilities (Tymms, 1999). Often academic performance is measured using standardized assessments (e.g., Bull et al., 2008; St.

Clair-Thompson & Gathercole, 2006). Studies utilizing such measures have found connections between cognitive processes, such as WM (e.g., Bull et al., 2008; St. Clair –Thompson & Gathercole, 2006) and academic achievement. Due to the expansive nature of academic achievement, I focused on two measures of math (fluency and calculation) and two measures of reading (fluency and passage comprehension) achievement. The following sections outline the literature relating academic achievement to WM and EM, in terms of behavioral and neural correlates.

3.1. Working Memory and Academic Achievement

WM has been examined numerous times in relation to math and reading achievement in children (e.g., Bull et al., 2008; Nevo & Bar-Kochva, 2015). Mental calculation has been suggested to be dependent on WM systems (Ashcraft, Donley, Halas, & Vakali, 1992; Furst & Hitch, 2000). Calculation is dependent on WM because the process of finding a calculation-based solution occurs within WM. For example, when solving the multiplication problem $6 x 3 = X$, a child has to maintain and monitor the representation of three 6s and manipulate this representation in order to come to a solution (i.e., 18). In addition to the manipulation of mathematical constructs, WM is also related to maintaining numerical representations (Geary, 1993; Kaufman, 2002).

WM is crucial for reading in addition to math achievement (Nevo & Bar-Kochva, 2015; for meta-analysis see Caretti, Borella, Cornoldi, & De Beni, 2009). WM is believed to maintain words online for conceptualization and comprehension of reading material or passages (Baddeley, 2004; Siegel, 1994). Without the ability to maintain words and word-meanings, comprehension would be lost. Behaviorally, WM has been suggested to influence reading achievement in multiple ways. For example, WM is predictive not only of overall reading comprehension but also of the abilities associated with reading comprehension such as decoding and vocabulary (Seigneuric, Ehrlich, Oakhill, & Yuill, 2000).

3.2. Episodic Memory and Academic Achievement

Clearly the connection between WM and academic achievement is well developed and justifiable. However, it is unlikely that WM is the only contributor to academic success. In fact, many studies suggest that cognitive processes, such as executive functioning (St. Clair-Thompson & Gathercole, 2006) or self-regulation (Duckswoth & Carlson, 2013), also influence academic achievement. General executive functioning, higher order cognitive control mechanisms, self-regulation, and temperamental effortful control, are all associated with WM (Hoffman, Schmeichel, & Baddeley, 2012; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). Therefore, additional constructs related to WM (i.e. EM) likely influence academic achievement.

WM and EM are theorized to work together to generate complex memory experiences (Baddeley, Allen, & Hitch, 2011). Therefore, it is likely that EM, in addition to WM, contributes to academic achievement. However, little research has been conducted examining the relation between EM and math and reading abilities. The literature that does exist has focused on the general construct of long- term memory (Swanson & Beebe-Frankenberger, 2004; Stevenson & Newman, 1986) rather than the specifically EM, or has examined EM in adolescents displaying academic delays (Mirandola, Del Prete, Ghetti, & Cornoldi, 2011).

Geary and colleagues (2008) proposed that mathematical fluency reduces the demands on WM when solving problems. It is possible that when children become more fluent on mathematical problems they begin to rely more on long-term memory processes rather than WM to solve problems. However, EM would also be necessary when first learning these concepts. It is also possible that WM operates as a mediator of the relation between EM and academic achievement in older children. During EM retrieval, EMs are brought into awareness within WM (Baddeley, 2000; Baddeley et al., 2011). It is therefore possible that EM, specifically retrieval processes, may benefit WM systems, which in turn influences academic achievement. This means that although the direct effect of EM on academic may dissipate with increased fluency, the indirect effect should remain stable regardless of level of fluency. Consequently, EM should be less likely to influence fluency measures of academic achievement in 9- versus 6-year-old children. I therefore examined both the direct and indirect effects of EM on math and reading measures of academic achievement at ages 6 and 9.

3.3. Recollection, Familiarity, and Academic Achievement

Recollection and familiarity are components of EM. So similar to EM, information regarding the relation between recollection, familiarity, and academic achievement is sparse. Mirandola and colleagues (2011) did examine recollection and familiarity in adolescents with and without reading difficulties. They reported that the poor learners, adolescents with learning difficulties, displayed a deficit in recollection but not familiarity. It is possible that although familiarity may be useful for multiple-choice assessments, recollection would be necessary for more effortful fill in the blank assessments in addition to being beneficial to multiple-choice assessments. However, these researchers did not consider other critical contributors to academic achievement, such as WM and intelligence (IQ), nor did they examine other measures of academic achievement.

To my knowledge, no studies exist examining the contributions of recollection and familiarity to performance on standardized tests of math achievements. However, the relation between recollection and math has been found indirectly through the use of recall tasks

(Stevenson & Newman, 1986). No studies thus far have directly compared recollection and familiarity to math achievement. Therefore, I examined the contributions of both recollection and familiarity, while controlling for IQ and WM, to both math and reading measures of academic achievement.

3.4. Neural Correlates of Academic Achievement in Relation to Working and Episodic Memory

Overlap exists in the neural correlates of math achievement, WM, and EM. In fact, the frontal or PFC activation found during calculation is often attributed to WM in children (Metcalfe, Ashkenazi, Rosenberg-Lee, & Menon, 2013; Supekar et al., 2013). Parietal activation during calculation has also been attributed to WM processes in addition to quantity representations (Metcalfe et al., 2013). The connections between EM and math achievement are less clear. Temporal activation during math processes has been found but has not been directly connected to EM. In general, temporal activation has been suggested to reflect explicit memory systems, and EM is a considered a type of explicit memory (Tulving, 2002; Tulving, 1972). However, it is apparent that the dominant explicit memory system discussed in relation to mathematical processing is semantic memory. Semantic memory is most often described as knowledge or fact based memory (Tulving, 1972). Semantic memory is most certainly involved in mathematical processing, but it likely that EM is also involved.

Similar to what was observed for math achievement, neural correlate overlap exists between WM, EM, and reading comprehension. Frontal and parietal activation during reading comprehension has been attributed to WM (King & Kutas, 1995; Turkeltaub et al., 2003). In addition to monitoring and manipulating information, WM may allow for interpretation of extended text in accordance with long-term memory systems, such as EM. Temporal activation patterns are observed during reading comprehension, but have been linked to semantic processing (Turkletaub et al., 2003). It is likely that reading comprehension requires both semantic and EM processes, as was proposed with mathematical processing. I therefore examined the contributions of both WM and EM neural correlates to math and reading achievement.

4. EEG Coherence and Power

Neural development in middle childhood is characterized by growth of neuronal connections, leading to enhanced cross-communication between neural regions. EEG coherence is a frequency-dependent squared cross-correlation of electrical signals obtained at two separate scalp electrode locations (Nunez, 1981). EEG coherence is non-invasive, and is often used when analyzing neural cross-communication during behavioral tasks, or functional connectivity in children (Bell & Cuevas, 2012). However, without stimulation, through exposure, it is unlikely that neuronal connections will form. Six year olds, in their first year of elementary school, should be less likely to have had the necessary exposure to math and reading lessons, and therefore less likely to have consistent use of these networks, to allow for the functional connectivity associated with more advance math and reading processes. Additionally, recent resting state MRI research examining connectivity suggests that cortico-cortical and cortico-subcortical connectivity increases with age, i.e. 7-19 years (Sole-Padulles, 2016). Furthermore, functional connectivity, assessed via fMRI and related to higher order cognitive functioning, has been suggested to be incomplete and fragmented in children between the ages of 6-8 years (de Bie et al., 2012). Nevertheless, the individual regions (temporal and frontal) involved in these tasks will likely show individual patterns of activation.

EEG power band analysis is another method used to examine EEG data. Power is interpreted to represent activation within individual scalp locations (Bell & Cuevas, 2012;

Pizzagalli, 2007). Different EEG frequencies, involving both power and coherence, are often related to cognitive ability. Increased activation in alpha (8-13 Hz), meaning decreased power, in frontal scalp locations has been associated with successful WM performance (Klimesch, 1999), whereas increases in theta activation (4-7 Hz), meaning increased power, within temporal regions have been associated with EM performance (Nyhus & Curran, 2010). I examined both theta and alpha coherence and power in 6 and 9 year olds.

5. Current Study

Many cognitive processes influence academic achievement. One such well-studied process is WM. EM, specifically recollection, is another cognitive process that likely relates to academic achievement; however, little is known about the relation between EM, and EM processes (i.e., recollection and familiarity), and academic achievement. In this study, I attempted to tease apart the influences of recollection and familiarity, while controlling for WM and IQ at age 6 and 9. This study was conducted longitudinally, eliminating confounds related to sample differences. Longitudinal analyses of these data allowed for insight into developmental differences. However, the data were treated cross-sectionally in order to answer questions specific to each age, as outlined in the hypotheses below. Later longitudinal analyses were conducted, but are beyond the scope of this study.

Additionally, there are possibly both direct and indirect (through WM) effects of recollection on academic achievement measures of math and reading that change as a result of fluency. At age 6, children are currently learning the basic principles of math and reading. The recency of their lessons will possibly lead to direct support from recollection when completing math and reading tasks, more so than what's observed in more advanced 9-year-old children. That being said, 9-year-old children may still benefit academically from strong recollection ability indirectly through WM, or through direct effects to more effortful achievement tasks (i.e. calculation and passage comprehension). Therefore, I will examine direct and indirect effects of recollection at age 6 and 9. Finally, neural correlate overlap exists between WM, EM, and academic achievement measures. I will examine the functional connectivity (frontotemporal coherence) as well as individual frontal and temporal activation (power) during recollection in relation to both the recollection task and academic achievement measures. Furthermore, frontal activation during WM will be examined in relation to both the WM task and academic achievement measures. The hypotheses are as follows:

Hypotheses:

1. Recollection will contribute to all four measures of academic achievement, over and above WM and IQ, at age 6. WM and IQ will contribute to all four measures in the same children at ages 6 and 9. Recollection will further contribute to the more effortful academic achievement measures (i.e. calculation and passage comprehension) at age 9. Familiarity will not contribute to academic achievement measures at ages 6 or 9.
2. Recollection and WM will have direct effects on all measures of academic achievement at age 6. WM will have direct effects on all measures of academic achievement at age 9. Recollection, however, will only have direct effects on the more effortful measures (i.e. calculation and passage comprehension). Additionally, recollection will have indirect effects, through WM, on all measures of academic achievement at ages 6 and 9.
3. Frontotemporal coherence, as well as frontal and temporal power, will contribute to recollection performance at age 9, but only power will contribute to recollection performance at age 6.
4. Frontal power will contribute to WM performance at ages 6 and 9.

5. Neural correlates of recollection and working memory will contribute to all four measures of academic achievement. However, functional connectivity during recollection will only contribute to age 9 academic achievement measures, not age 6.

Method

Participants

Age 6

Children (N=102) visited the research lab at age 6 (M = 6.81, SD = 0.60; 45% Male) as part of an ongoing longitudinal study exploring cognitive and emotional development. The children are predominately Caucasian (92%) with highly educated parents, with 87% of fathers and 96% of mothers completing some form of higher education. Some of the children have been part of an ongoing longitudinal study since infancy (N= 54) and the rest were newly recruited for the age 6 visit (N= 48). Four children were diagnosed with ADHD. These four children did not display any significant performance differences from the rest of the sample ($p>.05$), therefore, they were included in the analyses. As compensation for participation, at age 6, parents received a $50 gift certificate and children received a small gift and a $10 gift certificate.

Age 9

Children (N=78) visited the research lab again at age 9 (M = 9.51, SD = 0.50; 47% Male) as a continuation of the ongoing longitudinal grant. The children are predominately Caucasian (90%) with highly educated parents, with 88% of fathers and 96% of mothers completing some form of higher education. Some of the children have been part of an ongoing longitudinal study since infancy (N= 41), with 3 seen at age 9 but not 6, and the rest were newly recruited for the age 6 visit (N= 37). Nine of these children were diagnosed with ADHD, according to parent report. These children did not display any significant performance differences from the rest of the sample (p>.05); therefore, they were included in the analyses. This resulted in 76% retention from 6 to 9 in ongoing longitudinal participants and 77% retention from 6 to 9 in newly recruited participants. At age 9, parents received a $75 gift certificate and children will receive a $20 gift certificate, as well as a small gift.

Procedures

Participants visited our lab at age 6 during summer and fall of 2013. The same participants returned in the summer and fall of 2016 at age 9 for a continuation of our research lab's ongoing longitudinal study. Once consent and assent were given, participants were capped with an EEG cap and then given a series of cognitive, socioemotional, and achievement tasks. Only the tasks associated with my dissertation study are discussed. I focused on the WM, EM, and academic measures used in the larger longitudinal study. These tasks are outlined below. Of the tasks described, I designed the 9-year EM task, as well as the N-back task. All other tasks were previously part of the protocol.

EEG ages 6 and 9

EEG data were collected during both the EM and WM tasks, as well as during a video baseline. Recordings were made from 26 left, right, and midline scalp sites [frontal pole (Fp1, Fp2), frontal (F3, F4, Fz, F7, F8), central (C3, C4), central frontal (FC1, FC2, FC5, FC6), temporal (T7, T8), parietal (P3, P4, Pz, P7, P8), central parietal (CP1, CP2, CP5, CP6), occipital (O1, O2)]. All electrodes were referenced to Cz during the recordings. We recorded EEG using a stretch cap (Electro-Cap, Inc.; Eaton, OH; E1-series cap) with electrodes in the 10/20 system pattern. We placed a small amount of abrasive gel into each recording site and gently rubbed the scalp. We then added conductive gel to the recording sites. Electrode impedances were measured and accepted if they were below 20 KΩ. The electrical activity from each lead was amplified using separate James Long Company Bioamps (James Long Company; Caroga Lake, NY). The EEG activity for each scalp electrode was displayed on the monitor of the acquisition computer. The signal was digitized on-line at 512 samples per second for each channel in order to eliminate the effects of aliasing. This calibration signal was digitized for 30 seconds and stored for subsequent analysis. The acquisition software uses was Snapshot-Snapstream (HEM Data Corp., Southfield, MI) and the raw data was stored for later analyses.

EEG data were examined and analyzed using EEG Analysis software developed by the James Long Company. Average reference EEG data were then artifact scored for eye movements using a peak-to-peak criterion of 100µV or greater. Gross motor movements over 200µV peak to peak were also scored. These artifact-scored epochs were eliminated from all analyses. The data were then analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1 second width and 50% overlap. Coherence was computed for the theta 4-7 Hz and alpha 8-13 Hz band using an algorithm by Saltzberg, Burton, Burch, Fletcher, and Michaels (1986; equation 9). I focused on theta for the EM tasks and alpha for WM as justified in introduction. Based on research regarding EM and WM in childhood, I focused on frontal and temporal scalp locations in each hemisphere (F3/T7, F4/T8) in an attempt to capture frontal-temporal functioning connectivity during our EM task. Power values were also computed. Power was expressed as mean square microvolts and data were transformed using the natural log (ln) to normalize the distribution. Similarly to coherence, power was examined in frontal and temporal regions (F3, F4, F7, F8, T7, T8). EEG coherence and power were examined during encoding and retrieval conditions within each block of the memory task. Encoding EEG was collected during the presentation of each picture and then averaged across encoding sections. Retrieval EEG was collected during the presentation of each individual question and aggregated based on question type (i.e., *recollection and familiarity).* WM EEG was collected during each digit presentation and subsequent retrieval, and then averaged across digit span length.

Episodic Memory Task age 6

An adaptation of Corsi-Milner's (Milner et al., 1991) recognition memory task was employed as my EM task at age 6. This task was chosen because it includes both recollection (temporal order judgments) and familiarity ("pure" recognition) questions. To begin, two simple color drawings were presented on a computer screen, followed by the presentation of two practice questions. All children correctly answered the two questions. Then 40 color images were presented; each image remained on the screen for 4 seconds with no inter-trial interval. Occasionally, the sequence was interrupted and children were shown two images denoted as A and B. With the A and B images was a question that was read aloud by the experimenter, and answered aloud by the children. All answers were recorded immediately by the experimenter. Sometimes the question asked the children to indicate which image they had seen before and other times the question asked which picture they had seen last (see Figure 1 for examples of images and questions given). There were a total of 10 recognition questions (5 "seen before", 5 "seen last") and each participant received the same task presentation. The "seen before" questions measured familiarity and the "seen last" questions measured recollection. There were no restrictions in sampling for the questions (i.e., samples did not have to be part of the immediately preceding subset). The children were also given a delayed version of this task (5 "seen before", 5 "seen last") where they answered questions but were not presented with any additional pictures. The variables of interest were total familiarity and recollection correct within the immediate version of the task (see Table 1 for means and standard deviations).

Episodic Memory Task age 9

A revised version of the 6-year EM task was used at age 9. This task was again adapted from the original Corsi-Milner task (Milner et al., 1991). Standardized images from the Bank of Standardized Stimuli (BOSS; Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010) were used as stimuli in this task. For practice, three images were shown followed by a familiarity question (i.e. “Which of these images have you seen before?”). Participants repeated this sequence until they answered correctly. Once they completed the familiarity practice, they saw the same three images but were asked a recollection question (i.e. “Which of these images have you seen most recently?”). Again, the sequence was repeated until they answer correctly. Once the participants answered both the familiarity and recollection questions correctly and appeared to understand the task, they began the first block. The children answered the questions by pressing the appropriate computer key, and responses were saved into a text file that was later recorded by the experimenter (See Figure 2 for examples of images and questions given.)

There were four blocks of this task. Each block began with a presentation of 25 images, resulting in 100 images total, each shown for 1.5 seconds with a 1 second intertrial interval. Following the image presentation, participants were prompted to begin answering questions. The questions consisted of two images denoted with A or B and the participants indicated the correct answer using the keyboard. A total of 5 familiarity and 5 recollection questions were asked in each block, resulting in a total of 20 questions for each condition. The task was programed using SuperLab 4.5 (SuperLab Pro Edition) software developed by Cedrus, and the variables of interest were proportion correct for both familiarity and recollection questions (see Table 2 for means and standard deviations).

Working Memory Tasks ages 6 and 9

Backwards Digit Span. A backwards digit span task was administered at ages 6 and 9 to assess working memory (Garon et al., 2008). The experimenter initially read two digits aloud and children were instructed to verbally repeat the sequence backwards. Two practice trials were given to ensure understanding and then the task began. Attempt at recall of the same digit span with at least one correct trial for two trials was required before lengthening the span by one digit. The digit span was lengthened until errors were produced on two consecutive trials of the same span. Responses were recorded by the experimenter immediately as the child responded, and coded following the appointment. The variable of interest was digit span, which accounts for errors made in the trial previous to highest digit (see Tables 1 and 2 for means and standard deviations).

N-back. A 2-back task was administered at age 9. (It was not part of the age 6 protocol.) The 2-back task is often used during middle childhood and is considered a valid measure of WM (Ciesielski et al., 2006). The task was developed through combining strategies used by a number of studies (Ciesielski et al., 2006; Richards et al. 2009). Prior to beginning the trials, children practiced a series of 2-back designs, and understanding was reached before beginning the task. Each block consisted of 16 images of sea creatures, with 25% of the images requiring a response. Each image was shown for 2 seconds with an intertrial interval of 1 second. Children were instructed to identify a pattern and to press the spacebar whenever this pattern was identified. To elaborate, the children were told to press the spacebar if an image matched an image they saw two images earlier, a concrete example was shown before practice to aid in understanding. The task was coded based on correct responses, false alarms (incorrect responses), missed responses, and correct response reaction time. My variable of interest was the reaction time of correct responses (see Table 2 for means and standard deviations). Both WM measures (BD and N-back) at age 9 were standardized and made into a composite score to use as a single measure of WM.

Assessments of Math and Reading ages 6 and 9

Woodcock Johnson (WJ) III Tests of Achievement were used to measure math and reading achievement (Woodcock et al., 2001). Measures of math achievement included the subtests of calculation (Test 5) and math fluency (Test 6). The calculation section included math problems, of increasing difficulty. The math fluency section was timed (3 minutes), and children were asked to complete as many simple math calculations (e.g. 2+4) as possible. Measures of reading achievement included the subtests of passage comprehension (Test 9) and reading fluency (Test 2). The passage comprehension section required children read incomplete passages and decide on the word needed to fill in the blank so that the passage is comprehensible. The reading fluency section was times (3 minutes), and children were asked to decide if simple sentences were accurate or not (e.g. "The sky is always pink."). The variables of interest were number correct within each measure (see Tables 1 and 2 for means and standard deviations). The WJ III subtests demonstrate high reliabilities of .80 or higher (Nelson, Benner, Lane, & Smith, 2004).

Verbal IQ ages 6 and 9

The Peabody Picture Vocabulary Test IV (PPVT; Dunn & Dunn, 2012) was administered at age 6 and 9 as a proxy for Verbal IQ. Intelligence is typically correlated with EM, WM, and reading and math performance, so I controlled for this variable in my analyses. The PPVT is a nationally standardized instrument, and the measure of interest was participants' standardized scores (see Table 1 and 2 for means and standard deviations).

Results

For descriptive statistics and correlations see Tables 1, 2, 5, 6, 7, and 8 (age 6) and Tables 3, 4, 9, 10, 11, and 12 (age 9). Briefly, at age 6 children generated an average of 3.05 (SD = .80) digits on the BDS task. Performance on the recollection task (proportion correct; M = .74; SD =.26) differed from performance on the familiarity task (proportion correct; M=.85; SD=.21), $p \leq .001$. At age 9, children generated an average of 4.08 (SD =.82) digits on the BDS task, and had an average reaction time of 838.26 ms (SD = .202.85) on the N-back task. Performance on the recollection task (proportion correct; M = .67; SD = .12) differed from performance on the familiarity task (proportion correct; M = .92; SD = .10), $p \leq .001$.

For hypotheses 1 and 2, hierarchical regressions (8 total; 4 at age 6, 4 at age 9) were used to examine the contributions of recollection, familiarity, and working memory to the four academic achievement measures (i.e., reading comprehension, reading fluency, calculation, math fluency). For these regressions, Verbal IQ and WM performance were entered into the first step of each equation. These predictors were entered into the first step of the equation because they are known contributors to academic achievement. Recollection and familiarity performance were entered into the second step of the equation Path models (2 total; 1 at age 6, 1 at age 9) were used to further examine the direct and indirect effects of recollection and working memory on the academic achievement measures. In order to account for missing participants within the path models, Expectation-Maximization imputation was used to generate scores across variables. Lisrel Student edition 9.2 software was used to analyze the models, and SPSS software was used to examine the descriptive statistics of the variables of interest.

For hypothesis 3 and 4, four regressions were used to examine the contributions of frontotemporal coherence (F3T7 and F4T8; 2 regressions) and frontal and temporal power (F3, F4, T7, T8; 2 regressions) to recollection performance at age 6 and then 9. Two further regressions were used to examine the contributions of frontal power (F3, F4, F7, F8) to WM performance at age 6 and then 9. Twenty-four final regressions were used to examine the contributions of recollection (F3T7, F4T8; F3, F4, T7, T8) and working memory (F3, F4, F7, F8) neural correlates to all four measures of academic achievement at age 6 and then 9.

For hypothesis 5 and the regressions focused on the neural predictors of math and reading performance, baseline EEG (for WM) or encoding EEG (for recollection) were entered into the first step of the equation, and task EEG (WM or recollection) were entered into the second step of the equation. The electrode sites varied depending on the task analyzed (i.e., F3, F4, F7, F8 for WM; F3/T7, F4/T8, and F3, F4, T7, T8 for recollection).

Hypotheses 1 & 2
Behavioral Results for Reading and Math Achievement age 6

Passage comprehension. Verbal IQ and WM in Step 1 accounted for 26% of the variance in passage comprehension. The variables in Step 2 accounted for an additional 8% of the variance in passage comprehension, with Verbal IQ (6%), WM (13%), and recollection (6%) contributing unique variance (see Table 13a).

Reading fluency. Verbal IQ and WM in Step 1 accounted for 21% of the variance in reading fluency. The variables in Step 2 accounted for an additional 7% of the variance in reading fluency, with WM (11%) and recollection (5%), but not familiarity, contributing unique variance (see Table 13b).

Calculation. Verbal IQ and WM in Step 1 accounted for 23% of the variance in calculation. The variables in Step 2 accounted for an additional 4% of the variance in calculation, with WM (18%) and recollection (4%) contributing unique variance (see Table 13c)

Math fluency. Verbal IQ and WM in Step 1 accounted for 27% of the variance in math fluency. The variables in Step 2 accounted for an additional 5% of the variance in math fluency, with WM (20%) and recollection (4%) contributing unique variance (see Table 13d).

Path Model age 6. The hypothesized model was analyzed (see Figure 3). The fit indices were not indicative of a good fitting model, X^2 (6, N=102) = 344.40, p <.05, RMSEA = .74, CFI= .282, and GFI = .494, however, all direct and indirect paths were positive and significant (p<.05; see Table 21 and Figure 5).

Behavioral Results for Reading and Math Achievement age 9

Passage comprehension. Verbal IQ and WM in Step 1 accounted for 40% of the variance in passage comprehension. The variables in Step 2 accounted for an additional 3% of the variance in passage comprehension, with Verbal IQ (23%) contributing unique variance (see Table 14a).

Reading fluency. Verbal IQ and WM in Step 1 accounted for 24% of the variance in reading fluency. The variables in Step 2 accounted for an additional 2% of the variance in reading fluency, with Verbal IQ (14%) contributing unique variance (see Table 14b).

Calculation. Verbal IQ and WM in Step 1 accounted for 9% of the variance in calculation. The variables in Step 2 accounted for an additional 1% of the variance in calculation, no variables contributed unique variance to calculation performance (see Table 14c)

Math fluency. Verbal IQ and WM in Step 1 accounted for 6% of the variance in math fluency. The variables in Step 2 accounted for an additional 1% of the variance in math fluency, no variables contributed unique variance to calculation performance (see Table 14d).

Path Model age 9. The hypothesized model was analyzed (see Figure 4). The fit indices were not indicative of a good fitting model, X^2 (6, N=78) = 104.04, p <.05, RMSEA = .46, CFI= .209, and GFI = .703. The direct paths from EM and WM to passage comprehension were positive and significant (p<.05; see Table 22 and Figure 6). No other direct or indirect effects were significant.

Hypotheses 3 & 4:
Physiological Results for Recollection and Working Memory

The four regressions with frontotemporal coherence and frontal and temporal power predicting recollection performance at ages 6 and 9 were not significant. The working memory regressions are reported below.

Working Memory. Frontal baseline EEG (F3, F4, F7, F8) was entered into the first step and frontal EEG was entered into the second step of two regressions, one at age 6 and one at age 9. For the age 6 regression, frontal baseline EEG in Step 1 accounted for 8% of the variance in WM performance. The variables in Step 2 accounted for an additional 8% of the variance in WM performance; no variables contributed unique variance to WM performance (see Table 15). The age 9 regression was not significant.

Hypothesis 5:
Physiological Results for Reading and Math Achievement

Out of the 24 regressions using recollection and working memory EEG to predict academic achievement, two were significant (Fchange) at age 9. There were no significant age 6 regressions. Recollection and working memory EEG predicted math fluency, but no other measure of academic achievement at age 9. The significant age 9 regressions are reported below.

Math Fluency. Frontotemporal coherence (F3T7 and F4T8) Step 1 accounted for 3% of the variance in math fluency. The variables in Step 2 accounted for an additional 8% of the variance in math fluency, with left frontotemporal (F3T7) coherence during recollection contributing unique variance to math fluency performance (see Table 16).

Frontal baseline EEG in Step 1 accounted for 1% of the variance in math fluency performance. The variables in Step 2 accounted for an additional 7% of the variance in working memory performance, with left frontal (F7) EEG power during the working memory task contributing unique variance to math fluency performance (see Table 17).

Posthoc Analyses

Four exploratory path models, two at age 6 and two at age 9, were used to examine the further relations between recollection, working memory, and math and reading performance. Rather than including math and reading within the same model, they were separated. Math and reading were separated to increase the power, due to the low number of participants used in the models. I also separated math and reading due to the related nature of the constructs, and the inability to add additional paths with sufficient power. Furthermore, given issues with the age 9 variables, working memory only included the backwards digit span, no longer a composite, and EM was examined as a composite (both recollection and familiarity). These changes were made based on the lack of correlation between the N-back RT and digit span variables (r=.04), and the possibility that the recognition task elicited familiarity more so than recollection (see discussion for details). The results are outlined below.

Reading age 6. The initial model was similar to the hypothesized model, excluding math measures. Modification indices suggested the inclusion of a path from reading fluency to passage comprehension. Once this path was added, the once significant paths from working memory to passage comprehension, and recollection to passage comprehension were no longer significant. In order to further improve model fit, the paths from working memory to reading comprehension and recollection to passage comprehension were removed. Fit indices for the final model were indicative of a good fit, X^2 (2, N=102) = 2.02, p =.36, RMSEA = .01, CFI= 1.00., and GFI = .99. The direct paths from EM to reading fluency, EM to WM, WM to reading fluency, and reading fluency to passage comprehension were positive and significant (p<.05; see Table 23a and Figure 7). In terms of indirect effects, the indirect paths from WM and EM to passage comprehension were significant (p<.05). The indirect path from recollection to reading fluency was not significant.

Math age 6. The initial model was similar to the hypothesized model, excluding reading measures. Modification indices suggested the inclusion of a path from math fluency to calculation. Again, the inclusion of a path from math fluency to calculation resulted in a loss of significance of the paths from WM to calculation, and recollection to calculation. Fit indices for the final model were indicative of a good fit, X^2 (2, N=102) = 1.01, p =.60, RMSEA = .00, CFI= 1.00., and GFI = .99. The direct paths from EM to math fluency, EM to WM, WM to math fluency, and math fluency to calculation were positive and significant ($p<.05$; see Table 23b Figure 8). In terms of indirect effects, the indirect paths from WM and EM to calculation were significant ($p<.05$). The indirect path from recollection to math fluency was not significant.

Reading age 9. Again, the initial model was similar to the hypothesized model, excluding math measures. Modification indices suggested the inclusion of a path from reading fluency to passage comprehension. Once this path was added, the once significant path from working memory to passage comprehension dissipated, but the path from EM to passage comprehension remained. In order to improve model fit, the path from WM to passage comprehension was removed. Fit indices for the final model were mixed in terms of fit, with a X^2 (1, N=78) = 3.67, p =.06, RMSEA = .19, CFI= .96., and GFI = .98. Kaniskan and McCoach (2014) argued that RMSEA should not be considered when looking at models with small sample sizes and degrees of freedom, because in these situations RMSEA often falsely suggests a poor fitting model. Therefore, I will interpret this model as though it displayed adequate fit across fit indices. The direct paths from EM to reading fluency and comprehension, EM to WM, WM to reading fluency, and reading fluency to passage comprehension were positive and significant ($p<.05$; see Table 24a and Figure 9). In terms of indirect effects, the indirect paths from EM and WM to passage comprehension were significant ($p<.05$).. The indirect path from EM to reading fluency was not significant.

Math age 9. Again, the initial model was similar to the hypothesized model, excluding reading measures. The direct paths from EM to both calculation and math fluency were not significant. Furthermore, modification indices suggested the inclusion of a path from math fluency to calculation. In order to improve model fit, the direct paths from EM to calculation and math fluency were removed, and the paths from math fluency to calculation and WM to calculation were added. Fit indices for the final model were indicative of a good fit, X^2 (2, N=78) = 1.06, p =.59, RMSEA = .00, CFI= 1.00., and GFI = .99. The direct paths from EM to WM, and WM to reading fluency and calculation, and math fluency to calculation were positive and significant ($p<.05$; see Table 24b and Figure 10). The indirect paths of EM on calculation and math fluency, and WM on calculation were also significant ($p<.05$).

Discussion

I examined both behavioral and neural contributions to measures of academic achievement (math and reading) in the same children at ages 6 and 9. The results suggest that in addition to WM, recollection has a relation to both math and reading, however, this relation changes as a result of age. These results are consistent with past research examining WM contributions to academic achievement (Bull et al., 2008; Furst & Hitch, 2000) and the few studies examining the relation between recollection and academic achievement (Blankenship et al., 2015; Mirandola et al., 2011). I build on the existing literature by examining recollection, familiarity and WM simultaneously at multiple time points, and through the inclusion of neural contributors to academic achievement.

Hypothesis 1

For this project, EM was separated into recollection and familiarity in order to test differences related to their respective contributions to academic achievement. Given the prevalence of Verbal IQ and WM in the academic achievement literature the relation of WM to EM (Luciana & Nelson, 1998), I controlled for WM and Verbal IQ in my analyses. I hypothesized that at age 6 recollection, not familiarity, would contribute to all four measures of academic achievement. This portion of my hypothesis was supported. At age 6, recollection, but not familiarity, contributed to both math and reading performance, even after controlling for WM and Verbal IQ. This finding was expected given the research suggesting that recollection, not familiarity, is related to reading comprehension (Blankenship et al., 2015). This is the first study, however, to control for Verbal IQ and WM when examining the contributions of recollection and familiarity to reading achievement. Furthermore, this is the first study to examine the contributions of recollection and familiarity to math achievement.

I hypothesized that at age 9 recollection, not familiarity, would contribute to the more effortful measures of academic achievement (i.e., calculation and passage comprehension). This portion of my hypothesis was not supported. At age 9, neither recollection nor familiarity contributed to math or reading achievement. This result was not expected given the age 6 data, and previous studies showing a connection between recollection and academic achievement in 9 year olds (Blankenship et al., 2015) and adolescents (Mirandola et al., 2011). This may suggest that the direct relation between recollection and academic achievement dissipates from age 6 to 9. Perhaps older children are not as reliant on recollection when completing math and reading assessments. Another explanation is related to the math and reading assessments used. Although standardized assessments are appropriate when examining the relation between recollection and emerging math and reading achievement, maybe they are not appropriate for older children. To elaborate, since older children are exposed to a variety of different material throughout formal education, it is possible that the material presented on the standardized assessment is not recent enough to elicit recollection. A final explanation is related to the episodic memory task. To expand, the distance between presented images used in the recollection questions were controlled to limit difficulty. The 6-year data, and data from another cohort at age 9, suggested that a large distance (~10images) or a small distance (~2images) between images was too difficult for children to complete. In order to improve performance we constrained the distance between images. It is possible that I included too large of a distance between images. If this is the case, children may have relied on familiarity when completing the recollection questions, given that the pictures seen more recently would elicit greater familiarity than the previously viewed pictures.

Hypothesis 2

I hypothesized that at age 6 there would be a direct effect from recollection to working memory and that there would be direct effects from recollection and WM to all four measures of academic achievement. Furthermore, it was hypothesized that recollection would have an indirect effect through WM to all four measures of academic achievement. Although the overall model fit was poor, the pattern of results suggested that the individual paths were significant. Posthoc analyses were run to examine possible models.

Given the low number of participants, I examined two separate models for reading and math. As seen in the posthoc analyses, a few modifications were made to the 6-year models that resulted in adequate fit. A direct effect was found between WM and reading and math fluency. This result was expected given the relation of WM to both math and reading achievement (Bull et al., 2008; Furst & Hitch, 2000). Additionally, a direct effect was found from EM and both math and reading fluency. This result was hypothesized and suggests that EM impacts fluency measures of academic achievement directly. The direct effect from EM to comprehension was not significant, contrary to my hypothesis. The model suggested that reading and math fluency mediated the relation between WM and recollection to passage comprehension and calculation, respectively. This result was not hypothesized, but makes sense given the established relation between fluency and comprehension (e.g., Pikulski & Chard, 2005). Fluency is the ability to quickly and efficiently decode words and math problems; clearly these abilities influence calculation and reading comprehension, respectively. The mediating role of fluency on the relation between WM and comprehension and recollection and comprehension is less explored. The mathematical and reading representations that are brought forth when utilizing fluency would theoretically exist within WM, and the representations themselves likely originated within EM. This may explain why the indirect effect exists. An additional explanation is that the questions children were able to complete on the comprehension measures did not differ significantly from the questions on the fluency measures at age 6. To expand, for the passage comprehension and calculation subscales, children completed questions of ascending difficulty until they reached a level they were unable to complete. Therefore, it is likely that the questions children were able to complete on the comprehension measures were very similar to the questions they completed on the fluency measures. Furthermore the model suggested, as hypothesized, that indirect effects exist between recollection and all four measures of academic achievement through WM. This result suggests that at age 6, the effect of recollection on WM impacts academic achievement.

I hypothesized the same model used at age 6 at age 9, with the exception of the direct paths from recollection to both fluency measures (math and reading fluency). Within this model the overall fit and the individual paths were poor. Given the low number of participants and the results at age 6, I once again reran the models separating math and reading achievement.

Modifications were again made to the models, resulting in adequate fit. Changes were also made to the variables used in the 9-year analyses. To elaborate, the WM measure excluded N-back RT, given that RT is likely a measure of processing speed and not WM, and a composite EM score (recollection + familiarity) was used in place of recollection, given task spacing issues. Therefore the 9-year model examined EM while the 6-year model examined recollection, specifically. The patterns at age 9 differed from those found at age 6. Therefore, math and reading components will be discussed separately.

The path model examining reading achievement suggested that reading fluency mediated the path from WM to passage comprehension, with WM having a direct effect on reading fluency. Indirect paths also existed from EM to passage comprehension through both reading fluency and WM. Furthermore, EM displayed direct effects on both reading fluency and reading comprehension. The direct path from reading fluency to passage comprehension, and the indirect paths from WM and EM to passage comprehension, through reading fluency, were found at age 6 and 9. This result further supports the mediating role of reading fluency and suggests that both WM and EM influence reading fluency abilities throughout middle childhood, and that this relation impacts passage comprehension abilities. Of interest was the emergence of a direct path from EM to reading comprehension that was not present at age 6. This result provides evidence of a developmental difference and may suggest that children are more reliant on EM for reading comprehension at age 9 when compared to age 6. Furthermore, children at age 9 would be able to complete more difficult questions on the comprehension measures, thus requiring additional processes (i.e., EM).

I hypothesized that the direct effect of EM on reading fluency would dissipate by age 9; however, EM displayed a significant direct effect on reading fluency. This suggests that reading fluency continues to be impacted by EM throughout middle childhood. The dissipation effect may occur once children, or even adolescents, reach a peak in certain reading skills (e.g., grapheme-phoneme correspondence; Paris, 2005). Future studies should examine the relation between EM, specifically recollection, and reading fluency from childhood into adolescence. Alternatively, the relation between EM and reading fluency may never dissipate. EM may be beneficial to reading fluency throughout development. Clearly, further information is needed before such conclusions are drawn. Finally, the use of an EM composite may have altered the results, given that the EM task possibly tapped into familiarity more so than recollection. The direct and indirect paths from EM to passage comprehension were expected, and support my hypothesis that EM would have a direct and indirect effect on passage comprehension at age 9. This result suggests that EM impacts reading comprehension at multiple levels, both directly and through other processes (WM and reading fluency).

The path model examining math achievement did not show the mediation effect of WM observed in the other models. WM both directly and indirectly, through math fluency, impacted calculation at age 9, suggesting a partial but not full mediation. The difference in paths observed at age 6 and 9 may be a result of the abilities of the children and the difficulty of calculation problems. To elaborate, 9-year olds may be more reliant on WM when solving calculation problems because the problems they are able to complete require multiple steps, while 6 year olds are unable to complete such complex calculations. EM did not display any direct effects on math fluency or calculation, but did display indirect effects on both measures through WM. This result supports my hypothesis, with the exception of a direct path to calculation. These results along with the 9-year reading achievement results, suggests that EM may be more impactful to reading than math achievement during middle childhood. However, EM still displays indirect effects to math abilities through WM at age 9, meaning that the impact of EM on WM influences math abilities. Finally, a direct path from math fluency to calculation was found, further supporting the impact of math fluency on calculation.

Hypothesis 3

I hypothesized that frontotemporal coherence and power within these regions (frontal and temporal) would contribute to recollection performance at age 9, but that only power would contribute at age 6. My hypothesis was not supported; neither frontotemporal coherence nor power contributed to recollection performance at age 6 or 9. This result was unexpected given the literature supporting the role of these locations (Cabeza et al., 2002; Nyberg et al., 2003) and theta (Klimesch et al, 2001) in EM. One explanation is that the analyses were underpowered. The frontal and temporal power regressions had 8 predictors, which is above the recommended number of predictors for a regression using 78 participants (9 year; Knofczynski & Mundfrom, 2008) and is close to the limit at age 6. However, this does not explain why the results were not found for the coherence variables at age 9. The lack of coherence results may again be attributed to task design, if familiarity was measured more so than recollection it is possible that less connectivity between frontal and temporal regions would be necessary for successful performance, given that the hippocampus is necessary for recollection but not familiarity (Yonelinas, Otten, Shaw, & Rugg, 2005). Additional studies should explore the relation between EEG power and coherence at ages 6 and 9 using a revised EM task.

Hypothesis 4

I hypothesized that frontal power would contribute to WM performance at age 6 and 9. My results were partially supported with 6-year frontal EEG during both baseline and the WM task collectively predicting WM performance. This result was expected given the well established relation between frontal regions and WM (Smith & Jonides, 1999; Wolfe & Bell, 2004). The lack of individual predictors at age 6, and the lack of results at age 9, may again be a power issue. Another possible issue at age 9 is the use of RT for the N-back. To elaborate, at age 9, the WM measure was a composite of both the N-back RT and backwards digit span tasks, and as mentioned previously, RT likely measures processing speed more so than WM.

Hypothesis 5

I hypothesized that the power-based neural correlates of WM and recollection would contribute to all four measures of academic achievement at ages 6 and 9. Furthermore, I hypothesized that frontotemporal coherence during recollection would only contribute to the academic achievement measures at age 9. My results were not supported, with none of the EEG regressions significantly predicting academic achievement performance. To expand, while the F-change statistics were significant in the frontotemporal coherence (recollection) and frontal (WM) regressions to math fluency (Tables 16 and 17), the overall models were not. This was unexpected given past research suggesting a relation between frontal and temporal activation to both math (Supekar et al., 2013) and reading performance (Turkeltaub et al., 2003). Similar issues existed in these regressions as mentioned previously (i.e., underpowered, measurement issues). A further possible issue is the use of EEG during tasks other than the standardized assessments. To expand, I may have found frontal and temporal predictors if the EEG had been collected during the Woodcock Johnson assessments rather than the WM and EM tasks. Future studies should examine the contributions of frontal and temporal power and coherence during math and reading assessments.

Contributions, Limitations, and Future Directions

While the relation between WM and academic achievement is well developed, the relation between academic achievement and other memory systems is relatively unknown. This is the first study to examine the contributions of WM, recollection, and familiarity to math and reading achievement. I further examined how these relations change as a result of age. This study provides emerging evidence of developmental differences in the relations between WM and EM to math fluency, calculation, reading fluency, and passage comprehension. However, the significant path models were analyzed posthoc. Replication of these results is necessary before any conclusions may be drawn.

There were limitations with the recognition memory task used. One limitation, mentioned previously, was the spacing between images used in the recollection questions. Based on issues observed at age 6 and in another cohort of children at age 9, I controlled the distance between images. However, I did not test to ensure the distance was ideal to elicit recollection in children. Future studies should determine the distance needed to elicit recollection in childhood samples. Additionally, the task was sensitive to key presses and prone to skipping questions. This resulted in a number of voided trials. Future studies should attempt to control for similar program errors. Besides the recognition task, issues existed regarding the WM composite used at age 9. As mentioned previously, the use of RT during the N-back task may not have been an appropriate measure of WM. Future studies should utilize the number correct during the N-back task rather than the RT.

Summary and Conclusion

Few studies have examined the contributions of recollection and familiarity to academic achievement, and no studies have examined these processes while controlling for WM. Within the current study, EM, recollection at age 6, and WM contributed to academic achievement. Developmental differences were also observed from age 6 to 9 in terms of the relation between

EM and WM, to math (calculation and fluency) and reading (comprehension and fluency) achievement. These findings suggest that EM, recollection specifically, should be considered in addition to WM when examining academic achievement. While this study did not find a relation between frontal and temporal EEG activity and academic achievement, previous studies have found such relations (e.g., Turkeltaub et al., 2003), although the activation was not attributed to EM. Further research is needed to understand the behavioral and neural relations between recollection and academic achievement. Identifying the early contributors of academic achievement, and how they develop, may inform future interventions and educational policy.

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Table 1
6-year Behavioral Descriptive Statistics

	N	*Mean*	*SD*	*Min*	*Max*
Working Memory	101	3.05	.80	.00	4.50
Immediate Recollection	102	.74	.26	.00	*1.00*
Immediate Familiarity	102	.85	.21	.20	1.00
Verbal IQ	102	115.87	10.68	90.00	142.00
Reading Fluency	75	17.92	12.87	.00	48.00
Math Fluency	101	21.5	13.86	.00	63.00
Calculation	100	8.38	3.16	.00	16.00
Passage Comprehension	98	17.11	7.26	4.00	34.00

Table 2

6-year Physiological Descriptive Statistics

	N	*Mean*	*SD*	*Min*	*Max*
WM F3	99	3.01	.49	2.07	4.43
WM F4	99	2.97	.46	1.95	4.10
WM F7	99	2.95	.46	2.04	4.06
WM F8	99	2.96	.42	2.15	4.16
BL F3	101	2.94	.51	1.81	4.96
BL F4	101	2.92	.49	1.68	4.80
BL F7	101	2.81	.53	1.64	4.98
BL F8	101	2.80	.45	1.58	4.22
Recollection F3	*99*	3.30	.37	2.32	4.14
Recollection F4	99	3.30	.39	2.46	4.15
Recollection T7	97	3.22	.45	1.71	4.38
Recollection T8	97	3.24	.43	2.01	4.12
Encoding F3	99	3.30	.37	2.32	4.14
Encoding F4	99	3.30	.39	2.46	4.15
Encoding T7	97	3.22	.45	1.71	4.38
Encoding T8	97	3.24	.43	2.01	4.12
Recollection F3T7	97	.12	.07	.002	.34
Recollection F4T8	97	.13	.10	.02	.82
Encoding F3T7	96	.09	.05	.01	.25
Encoding F4T8	96	.09	.06	.001	.35

Note: WM is working memory and BL is baseline.

Table 3
9-year Behavioral Descriptive Statistics

	N	*Mean*	*SD*	*Min*	*Max*
Backwards Digit Span	78	4.08	.82	2.00	6.00
N-back RT (ms)	74	838.26	202.85	442.63	1263.33
Immediate Recollection	78	.67	.12	.20	.90
Immediate Familiarity	78	.92	.10	.47	1.00
Verbal IQ	78	117.06	13.28	92.00	158.00
Reading Fluency	77	43.27	13.25	21.00	78.00
Math Fluency	77	54.49	20.05	15.00	108.00
Calculation	77	18.26	3.32	12.00	26.00
Passage Comprehension	77	30.30	4.38	17.00	41.00

Table 4
9-year Physiological Descriptive Statistics

	N	*Mean*	*SD*	*Min*	*Max*
WM F3	75	2 .84	.46	1.65	4.29
WM F4	75	2.85	.43	1.81	3.77
WM F7	74	2.99	.46	2.05	4.02
WM F8	74	2.96	.43	2.12	4.18
BL F3	77	2.70	.47	1.31	4.07
BL F4	77	2.73	.46	1.47	4.13
BL F7	77	2.77	.44	1.90	4.02
BL F8	77	2.71	.41	1.85	3.81
Recollection F3	77	3.18	.34	2.39	4.15
Recollection F4	77	3.21	.33	2.47	4.00
Recollection T7	76	3.42	.43	1.94	4.42
Recollection T8	76	3.37	.43	1.88	4.49
Encoding F3	77	3.13	.32	2.35	3.84
Encoding F4	77	3.17	.32	2.36	3.93
Encoding T7	76	3.28	.46	1.80	4.59
Encoding T8	76	3.26	.42	1.71	4.23
Recollection F3T7	76	.09	.06	.01	.34
Recollection F4T8	76	.09	.05	.01	.28
Encoding F3T7	76	.12	.07	.01	.33
Encoding F4T8	76	.11	.06	.00	.25

Note: WM is working memory and BL is baseline.

Table 5

6-year Behavioral Correlations

Variables	1	2	3	4	5	6	7	8
1. WM	--							
2. Recollection	.193^{+}	--						
3. Familiarity	.073	-.165	--					
4. Verbal IQ	.154	.042	.114	--				
5. Reading Fluency	.412***	.286*	.206	.222^{+}	--			
6. Math Fluency	.519***	.324**	.010	.158	.624***	--		
7. Calculation	.417***	.271**	.070	.146	.587***	.836***	--	
8. Passage Comp.	.449***	.290**	.166	.314**	.876***	.718***	.766***	--

Note: *** p $\leq$. 001; ** p$\leq$.01; *p$\leq$.05; +p$\leq$.06; WM is working memory and comp is comprehension.

Table 6
6-Year Working Memory Behavioral and Physiological Correlations

Variables	1	2	3	4	5
1. WM	--				
2. WM F3	-.280**	--			
3. WM F4	-.265**	.927***	--		
4. WM F7	-.177	.880***	.889***	--	
5. WM F8	-.129	.814***	.852***	.916***	--

Note: *** p ≤. 001; ** p≤.01; WM is working memory.

Table 7
6-Year Recollection Behavioral and Physiological Correlations

Variables	1	2	3	4	5	6	7
1. Recollection	--						
2. Recollection F3	.108	--					
3. Recollection F4	.100	.800***	--				
4. Recollection T7	.115	.600***	.728***	--			
5. Recollection T8	.088	.745***	.708***	.781***	--		
6. Recollection F3T7	.046	-.300**	-.186	-.191	-.285**	--	
7. Recollection F4T8	.052	-.375***	-.056	.044	-.131	.291**	--

Note: *** p ≤. 001

Table 8

6-Year Academic Achievement Behavioral and Physiological Correlations

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Reading Fluency	--													
2. Math Fluency	.624***	--												
3. Calculation	.587***	.836***	--											
4. Passage Comp.	.876***	.718***	.766***	--										
5. WM F3	-.121	-.184	-.208***	-.112	--									
6. WM F4	-.083	-.169	-.190	-.081	.927***	--								
7. WM F7	-.124	-.135	-.185	-.096	.880***	.889***	--							
8. WM F8	-.075	-.083	-.140	-.020	.814***	.852***	.916***	--						
9. Recollection F3	-.188	-.207*	-.169	-.081	.719***	.677***	.635***	.587***	--					
10. Recollection F4	-.090	-.132	-.040	.047	.667***	.706***	.644***	.603***	.800***	--				
11. Recollection T7	.064	-.125	-.110	.007	.562***	.636***	.634***	.599***	.600***	.728***	--			
12. Recollection T8	-.033	-.157	-.143	.005	.666***	.690***	.689***	.675***	.745***	.708***	.781***	--		
13. Recollection F3T7	.034	.108	.182	.053	-.253*	-.283**	-.164	-.246*	-.300**	-.186	-.191	-.285**	--	
14. Recollection F4T8	.166	.081	.116	.045	-.111	-.137	-.086	-.134	-.375***	-.056	.044	-.131	.291**	--

Note: *** p ≤. 001; ** p≤.01; *p≤.05; WM is working memory and comp is comprehension.

Table 9

9-year Behavioral Correlations

Variables	1	2	3	4	5	6	7	8
1. WM Composite	--							
2. Recollection	.163	--						
3. Familiarity	.295**	.412***	--					
4. Verbal IQ	.228*	.209	.287*	--				
5. Reading Fluency	.225*	.205	.293**	.469***	--			
6. Math Fluency	.217	.141	.101	.153	.599***	--		
7. Calculation	.231*	.177	.158	.240*	.453***	.536***	--	
8. Passage Comp.	.322**	.289*	.335**	.601**	.615***	.230*	.475***	--

Note: *** p ≤. 001; ** p≤.01; *p≤.05; WM is working memory and comp is comprehension.

Table 10

9-Year Working Memory Behavioral and Physiological Correlations

Variables	1	2	3	4	5
1. WM Composite	--				
2. WM F3	.145	--			
3. WM F4	.085	.916***	--		
4. WM F7	.107	.884***	.868***	--	
5. WM F8	.043	.854***	.878***	.943***	--

Note: *** $p \leq .001$; WM is working memory.

Table 11
9-Year Recollection Behavioral and Physiological Correlations

Variables	1	2	3	4	5	6	7
1. Recollection	--						
2. Recollection F3	.096	--					
3. Recollection F4	.000	.879***	--				
4. Recollection T7	-.018	.616***	.658***	--			
5. Recollection T8	.002	.686***	.728***	.828***	--		
6. Recollection F3T7	.028	.013	-.096	-.127	-.119	--	
7. Recollection F4T8	.052	.042	-.009	.028	-.006	.388***	--

Note: *** p ≤. 001

Table 12

9-Year Academic Achievement Behavioral and Physiological Correlations

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Reading Fluency	--													
2. Math Fluency	.599***	--												
3. Calculation	.453***	.536***	--											
4. Passage Comp.	.615***	.230*	.475***	--										
5. WM F3	-.113	-.053	-.112	-.099	--									
6. WM F4	-.128	-.112	-.147	-.200	.916***	--								
7. WM F7	.005	.020	-.151	-.039	.884***	.868***	--							
8. WM F8	-.059	-.060	-.206	-.088	.854***	.878***	.943***	--						
9. Recollection F3	-.080	-.066	-.149	-.072	.845***	.785***	.767***	.729***	--					
10. Recollection F4	-.099	-.136	-.218	-.152	.760***	.813***	.749***	.731***	.879***	--				
11. Recollection T7	.103	-.049	-.184	.070	.593***	.605***	.746***	.665***	.616***	.658***	--			
12. Recollection T8	-.007	-.098	-.163	.008	.693***	.674***	.802***	.770***	.686***	.726***	.828***	--		
13. Recollection F3T7	.030	.116	.034	.025	-.169	-.228*	-.187	-.204	.013	-.096	-.127	-.119	--	
14. Recollection F4T8	.091	-.074	-.171	.006	-.077	-.103	-.025	-.051	.042	-.009	.028	-.006	.388***	--

Note: *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; WM is working memory and comp is comprehension.

Table 13

Hierarchical Regression Analyses of Memory Predicting Academic Achievement at age 6

	R	R^2	$R^2\Delta$	*FΔ*	*F*	*β*	*t*	sr^2
a. Reading Comprehension								
Step 1.	.52	.26			17.35***			
Verbal IQ						.26	2.92**	.07
Working Memory						.41	4.68***	.17
Step 2.	.59	.34	.08	5.28**	12.09***			
Verbal IQ						.25	2.87**	.06
Working Memory						.36	4.22***	.13
Recollection						.26	2.94**	.06
Familiarity						.17	1.94	.03
b. Reading Fluency								
Step 1.	.46	.21			9.66***			
Verbal IQ						.21	1.96	.04
Working Memory						.40	3.85***	.16
Step 2.	.52	.28	.07	3.42*	6.86***			
Verbal IQ						.17	1.62	.03
Working Memory						.34	3.24**	.11
Recollection						.23	2.18*	.05
Familiarity						.19	1.79	.03
c. Calculation								
Step 1.	.48	.23			14.38***			
Verbal IQ						.08	.92	.01
Working Memory						.46	5.11***	.21
Step 2.	.52	.27	.04	2.60	8.73***			
Verbal IQ						.08	.88	.01
Working Memory						.42	4.62***	.18
Recollection						.20	2.24*	.04
Familiarity						.08	.83	.01
d. Math Fluency								
Step 1.	.52	.27			18.17***			
Verbal IQ						.06	.67	.00
Working Memory						.51	5.82***	.25
Step 2.	.56	.32	.05	3.20*	11.09***			
Verbal IQ						.06	.69	.00
Working Memory						.47	5.32***	.20
Recollection						.22	2.49*	.04
Familiarity						.00	.03	.00

Note: *** $p \leq .001$; ** $p \leq .01$; *$p \leq .05$

Table 14

Hierarchical Regression Analyses of Memory Predicting Academic Achievement at age 9

	R	R^2	$R^2\Delta$	*FΔ*	*F*	*β*	*t*	sr^2
a. Reading Comprehension								
Step 1.	.63	.40			24.36***			
Verbal IQ						.56	6.00***	.29
Working Memory						.20	2.11*	.04
Step 2.	.65	.43	.03	1.85	13.39***			
Verbal IQ						.51	5.38***	.23
Working Memory						.16	1.74	.02
Recollection						.12	1.21	.01
Familiarity						.10	.97	.01
b. Reading Fluency								
Step 1.	.49	.24			11.36***			
Verbal IQ						.44	4.22***	.18
Working Memory						.13	1.20	.01
Step 2.	.51	.26	.02	1.12	6.26***			
Verbal IQ						.40	3.70***	.14
Working Memory						.09	.86	.01
Recollection						.05	.48	.00
Familiarity						.13	1.15	.01
c. Calculation								
Step 1.	.30	.09			3.69*			
Verbal IQ						.20	1.74	.04
Working Memory						.19	5.64	.03
Step 2.	.32	.10	.01	.51	2.07			
Verbal IQ						.17	1.46	.03
Working Memory						.17	1.45	.03
Recollection						.11	.87	.01
Familiarity						.02	.17	.00
d. Math Fluency								
Step 1.	.24	.06			2.30			
Verbal IQ						.11	.94	.01
Working Memory						.19	1.66	.03
Step 2.	.26	.07	.01	.33	1.29			
Verbal IQ						.09	.78	.01
Working Memory						.18	1.54	.03
Recollection						.10	.79	.01
Familiarity						-.01	-.11	.00

Note: *** p $\leq$. 001; ** p$\leq$.01; *p$\leq$.05

Table 15
Hierarchical Regression of Frontal Power Predicting Working Memory Performance at age 6

	R	R^2	$R^2\Delta$	*FΔ*	*F*	*β*	*t*	sr^2
Step 1.	.28	.08			1.99			
F3 Baseline EEG						-.80	-2.02*	.04
F4 Baseline EEG						.12	.31	.00
F7 Baseline EEG						.33	.83	.01
F8 Baseline EEG						.22	.74	.00
Step 2.	.40	.16	.08	2.29	2.20*			
F3 Baseline EEG						-.62	-1.36	.02
F4 Baseline EEG						.56	1.21	.01
F7 Baseline EEG						.09	.22	.00
F8 Baseline EEG						.17	.54	.00
F3 WM EEG						-.09	-.28	.00
F4 WM EEG						-.60	-1.76	.03
F7 WM EEG						.01	.03	.00
F8 WM EEG						.29	1.06	.01

Note: *p≤.05; F is frontal.

Table 16

Hierarchical Regression of Temporal Recollection Coherence Predicting Math Fluency at age 9

	R	R^2	$R^2\Delta$	$F\Delta$	*F*	β	*t*	sr^2
Step 1.	.17	.03			1.13			
F3T7 Encoding EEG						.17	1.36	.02
F4T8 Encoding EEG						-.14	-1.12	.02
Step 2.	.33	.11	.08	3.23*	2.21			
F3T7 Encoding EEG						.07	.52	.00
F4T8 Encoding EEG						-.21	-1.52	.03
F3T7 Retrieval EEG						.32	2.53*	.08
F4T8 Retrieval EEG						.00	.00	.00

Note: *p≤.05; F is frontal and T is temporal.

Table 17

Hierarchical Regression of Frontal Working Memory Power Predicting Math Fluency at age 9

	R	R^2	$R^2\Delta$	*F*Δ	*F*	*β*	*t*	sr^2
Step 1.	.09	.01			.12			
F3 Baseline EEG						-.15	-.39	.00
F4 Baseline EEG						.09	.24	.00
F7 Baseline EEG						.03	.06	.00
F8 Baseline EEG						-.04	-.09	.00
Step 2.	.42	.18	.07	3.28*	1.71			
F3 Baseline EEG						.18	.36	.00
F4 Baseline EEG						.47	1.14	.02
F7 Baseline EEG						-1.00	-1.87	.04
F8 Baseline EEG						.03	.08	.00
F3 WM EEG						-.08	-.17	.00
F4 WM EEG						-.62	-1.56	.03
F7 WM EEG						1.64	2.96**	.11
F8 WM EEG						-.70	-1.62	.03

Note: *p≤.05; WM is working memory and F is frontal.

Table 18

6-year Correlations and Standard Deviations following imputation

Variables	1	2	3	4	5	6
1. WM	--					
2. Recollection	.202	--				
3. Passage Comprehension	.471	.313	--			
4. Reading Fluency	.487	.287	.927	--		
5. Calculation	.486	.287	.775	.729	--	
6. Math Fluency	.524	.324	.729	.747	.843	--
SD	.794	.261	7.262	14.388	3.200	13.792

Note: These values were used in both hypothesized and posthoc analyses.

Table 19

9-year Correlations and Standard Deviations following imputation with WM composite and Recollection

Variables	1	2	3	4	5	6
1. WM composite	--					
2. Recollection	.163	--				
3. Passage Comprehension	.333	.294	--			
4. Reading Fluency	.233	.208	.617	--		
5. Calculation	.239	.181	.478	.456	--	
6. Math Fluency	.225	.145	.234	.601	.538	--
SD	.741	.125	4.370	13.191	3.304	19.960

Note: These values were used in the hypothesis analysis only. WM is working memory and SD is standard deviation.

Table 20

9-year Correlations and Standard Deviations following imputation with EM composite and without WM composite

Variables	1	2	3	4	5	6
1. WM	--					
2. EM	.266	--				
3. Passage Comprehension	.410	.378	--			
4. Reading Fluency	.367	.298	.622	--		
5. Calculation	.434	.216	.485	.462	--	
6. Math Fluency	.406	.161	.243	.605	.544	--
SD	.819	.093	4.384	13.264	3.327	20.075

Note: These values were used in the posthoc analysis only. WM is working memory, EM is episodic memory, and SD is standard deviation.

Table 21

Factor loadings, errors, and multiple squared correlations for hypothesized 6-year Model

	Direct effect	*Indirect effect*	*Total effect*	R^2	*error*
Dependent variable: Working Memory				.04	.96
1. Recollection	.20*	--	.20*		
Dependent variable: Passage Comprehension				.27	.73
1. Recollection	.23*	.09	.31***		
2. Working Memory	.43***	--	.43***		
Dependent variable: Reading Fluency				.27	.73
1. Recollection	.20*	.09	.29**		
2. Working Memory	.45***	--	.45***		
Dependent variable: Calculation				.27	.73
1. Recollection	.20*	.09	.29**		
2. Working Memory	.45***	--	.45***		
Dependent variable: Math Fluency				.32	.68
1. Recollection	.23*	.10	.32***		
2. Working Memory	.48***	--	.48***		

Note: * $p \leq .05$ ** $p \leq .01$ *** $p \leq .001$. Completely standardized solutions presented.

Table 22
Factor loadings, errors, and multiple squared correlations for hypothesized 9-year Model

	Direct effect	*Indirect effect*	*Total effect*	R^2	*error*
Dependent variable: Working Memory				.03	.97
2. Recollection	.16	--	.16		
Dependent variable: Passage Comprehension				.17	.83
3. Recollection	.25*	.05	.29*		
4. Working Memory	.29*	--	.29*		
Dependent variable: Reading Fluency				.08	.92
3. Recollection	.18	.03	.21		
4. Working Memory	.21	--	.45***		
Dependent variable: Calculation				.08	.92
3. Recollection	.15	.04	.18		
4. Working Memory	.22	--	.45***		
Dependent variable: Math Fluency				.06	.94
3. Recollection	.11	.03	.15		
4. Working Memory	.21	--	.48***		

Note: * $p \leq .05$ ** $p \leq .01$ *** $p \leq .001$. Completely standardized solutions presented.

Table 23

Factor loadings, errors, and multiple squared correlations for posthoc 6-year Models

	Direct effect	*Indirect effect*	*Total effect*	*R^2*	*error*
a. Reading Achievement					
Dependent variable: Working Memory				.04	.96
3. Recollection	.20*	--	.20*		
Dependent variable: Passage Comprehension				.86	.14
5. Reading Fluency	.93***	--	.93***		
6. Recollection	--	.27**	.27**		
7. Working Memory	--	.42***	.42***		
Dependent variable: Reading Fluency				.27	.73
5. Recollection	.20*	.09	.29**		
6. Working Memory	.45***	--	.45***		
b. Math Achievement					
Dependent variable: Working Memory				.04	.96
4. Recollection	.20*	--	.20*		
Dependent variable: Calculation				.71	.29
8. Math Fluency	.84***	--	.84***		
9. Recollection	--	.27**	.27**		
10. Working Memory	--	.40***	.40***		
Dependent variable: Math Fluency				.32	.68
7. Recollection	.23**	.10	.32***		
8. Working Memory	.48***	--	.48***		

Note: * $p \leq .05$ ** $p \leq .01$ *** $p \leq .001$. Completely standardized solutions presented.

Table 24

Factor loadings, errors, and multiple squared correlations for posthoc 9-year Models

	Direct effect	*Indirect effect*	*Total effect*	R^2	*error*
a. Reading Achievement					
Dependent variable: Working Memory				.07	.93
5. Episodic Memory	.27*	--	.27*		
Dependent variable: Passage Comprehension				.43	.57
11. Reading Fluency	.56***	--	.56***		
12. Episodic Memory	.21*	.17*	.38**		
13. Working Memory	--	.17**	.17**		
Dependent variable: Reading Fluency				.18	.82
9. Episodic Memory	.22*	.08	.30**		
10. Working Memory	.31**	--	.31***		
b. Math Achievement					
Dependent variable: Working Memory				.07	.93
6. Episodic Memory	.27*	--	.27*		
Dependent variable: Calculation				.35	.65
14. Math Fluency	.44***	--	.44***		
15. Episodic Memory	--	.12*	.12*		
16. Working Memory	.26*	.18**	.43***		
Dependent variable: Math Fluency				.17	.83
11. Episodic Memory		.11*	.11*		
12. Working Memory	.41***	--	.41***		

Note: * $p \leq .05$ ** $p \leq .01$ *** $p \leq .001$. Completely standardized solutions presented.

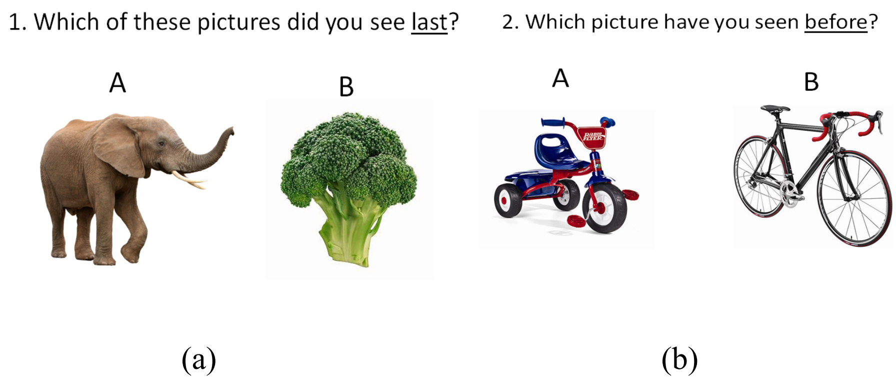
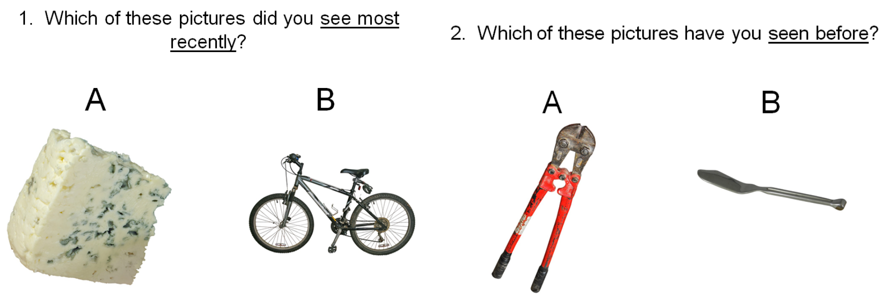


Figure 1: Examples of questions given in 6-year EM task. 1a is an example of a recollection question, while 1b is familiarity.



(a) (b)

Figure 2: Examples of questions given in 9-year EM task.1a is an example of a recollection question, while 1b is familiarity.

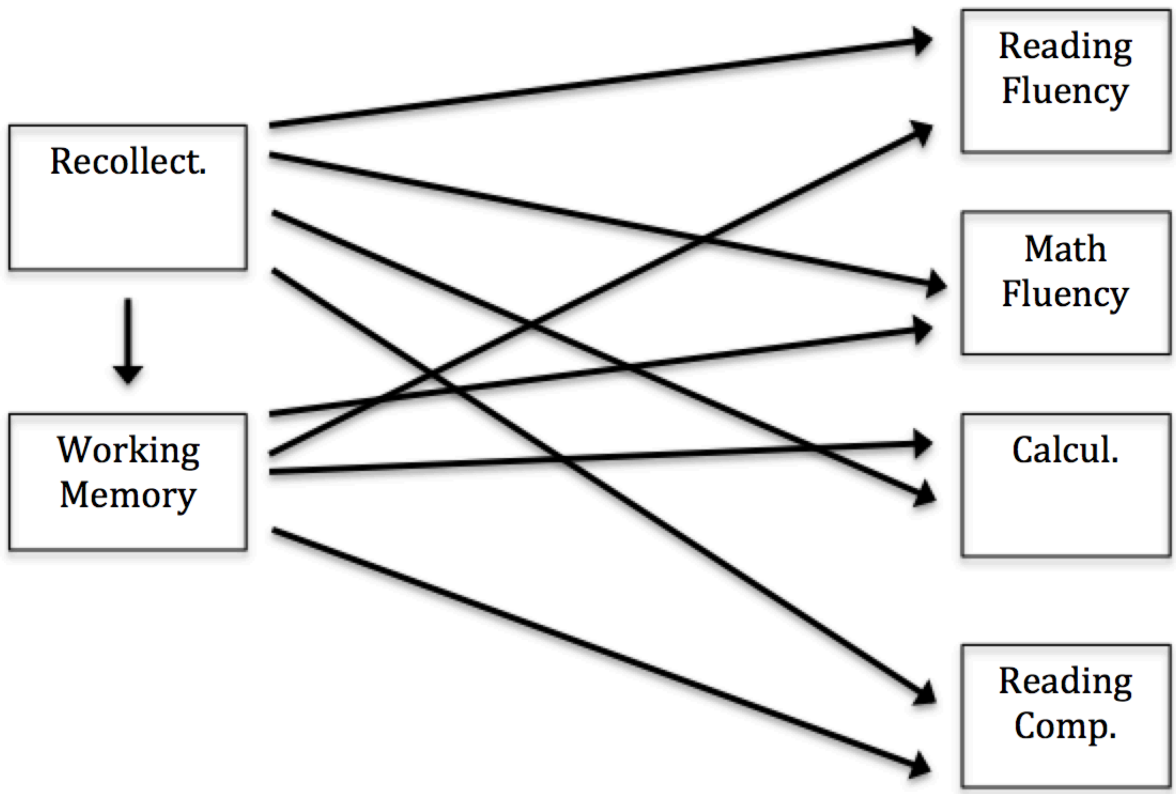


Figure 3: Hypothesized path model for recollection and working memory on the four measures of academic achievement at age 6. Note: calcul. is calculation and reading comp. is reading comprehension.

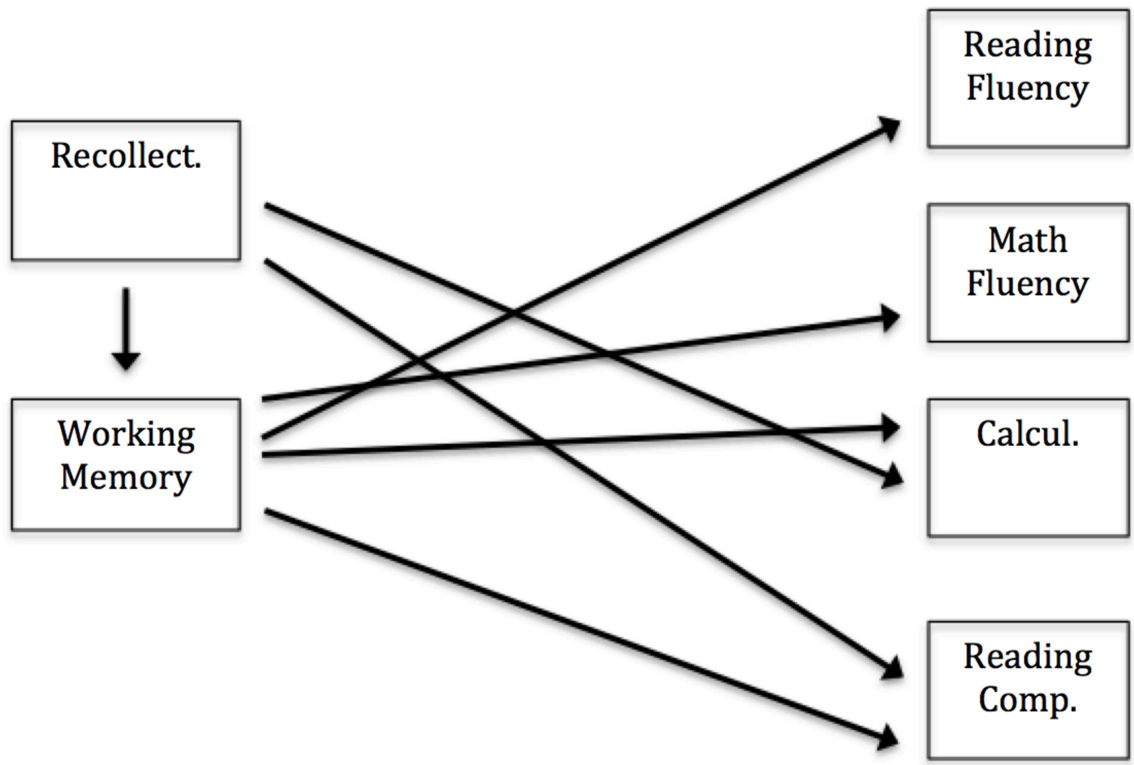
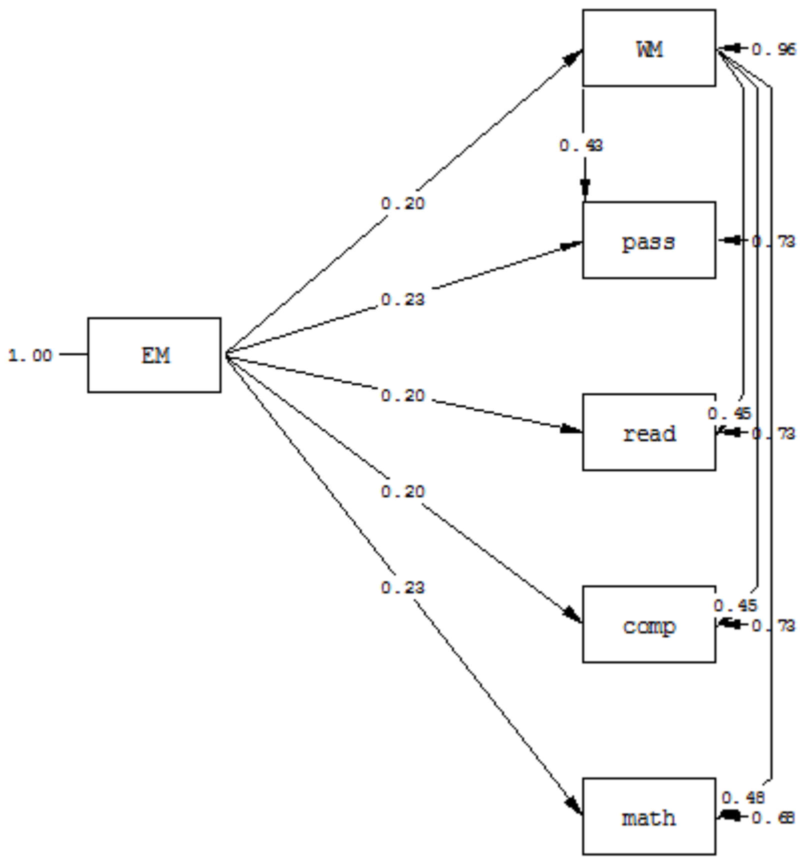


Figure 4: Hypothesized path model for recollection and working memory on the four measures of academic achievement at age 9. Note: calcul. is calculation and reading comp. is reading comprehension.



Chi-Square=344.40, df=6, P-value=0.00000, RMSEA=0.744

Figure 5: Hypothesized path model for recollection and working memory on the four measures of academic achievement at age 6. Note: EM is episodic memory, WM is working memory, pass is passage comprehension, read is reading fluency, comp is calculation, and math is math fluency.

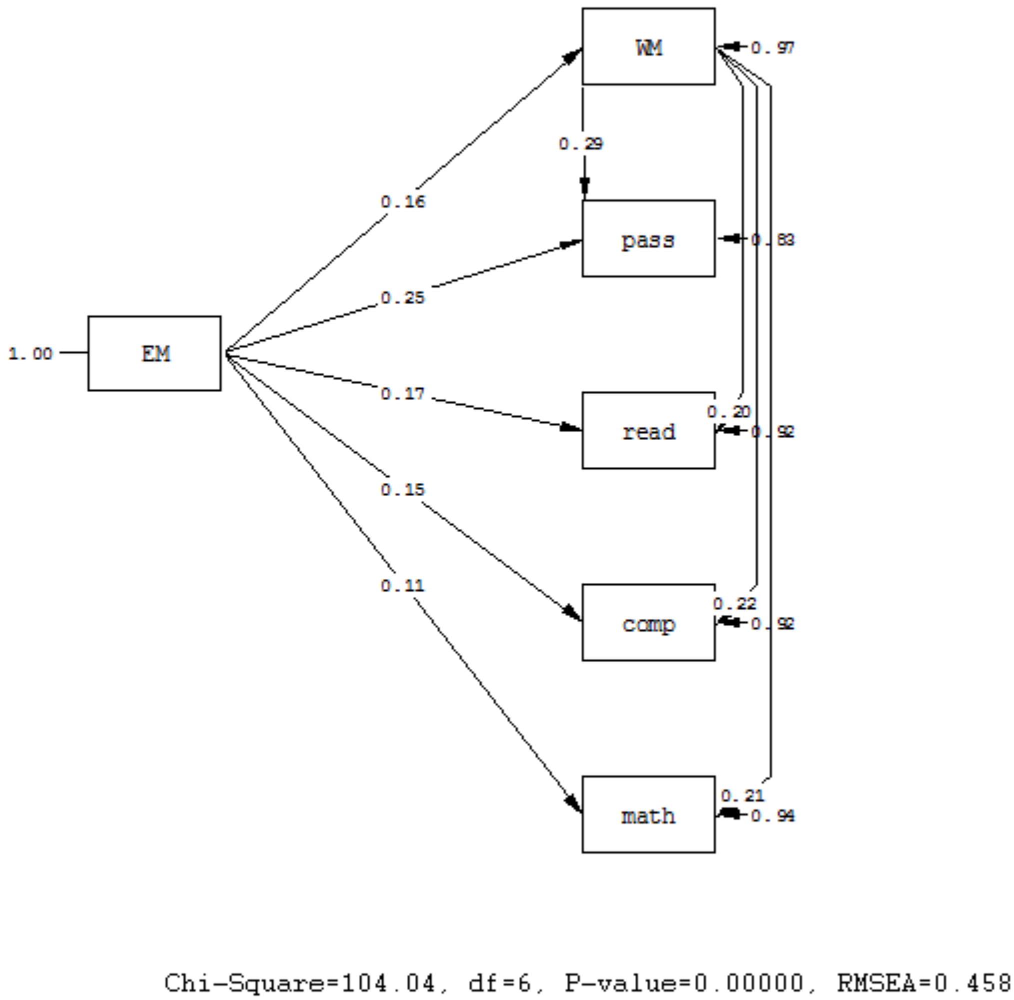


Figure 6: Hypothesized path model for recollection and working memory on the four measures of academic achievement at age 9. Note: EM is episodic memory, WM is working memory, pass is passage comprehension, read is reading fluency, comp is calculation, and math is math fluency.

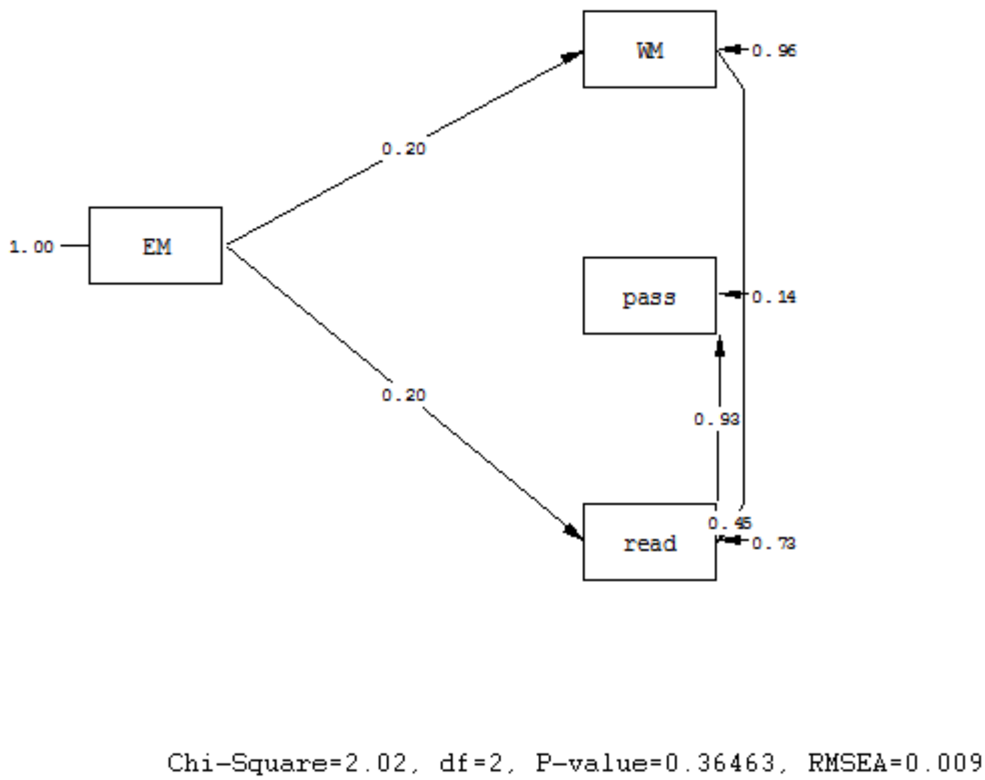


Figure 7: Posthoc path model for recollection and working memory on reading achievement at age 6. Note: EM is episodic memory, WM is working memory, pass is passage comprehension, and read is reading fluency.

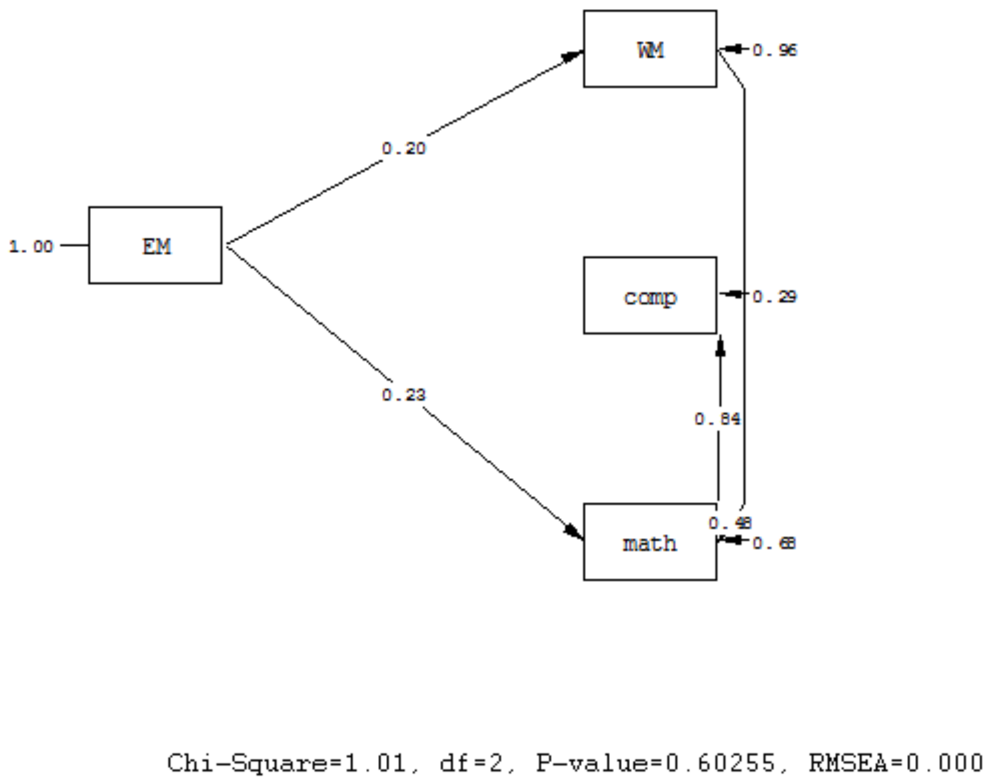


Figure 8: Posthoc path model for recollection and working memory on math achievement at age 6. Note: EM is episodic memory, WM is working memory, comp is calculation, and math is math fluency.

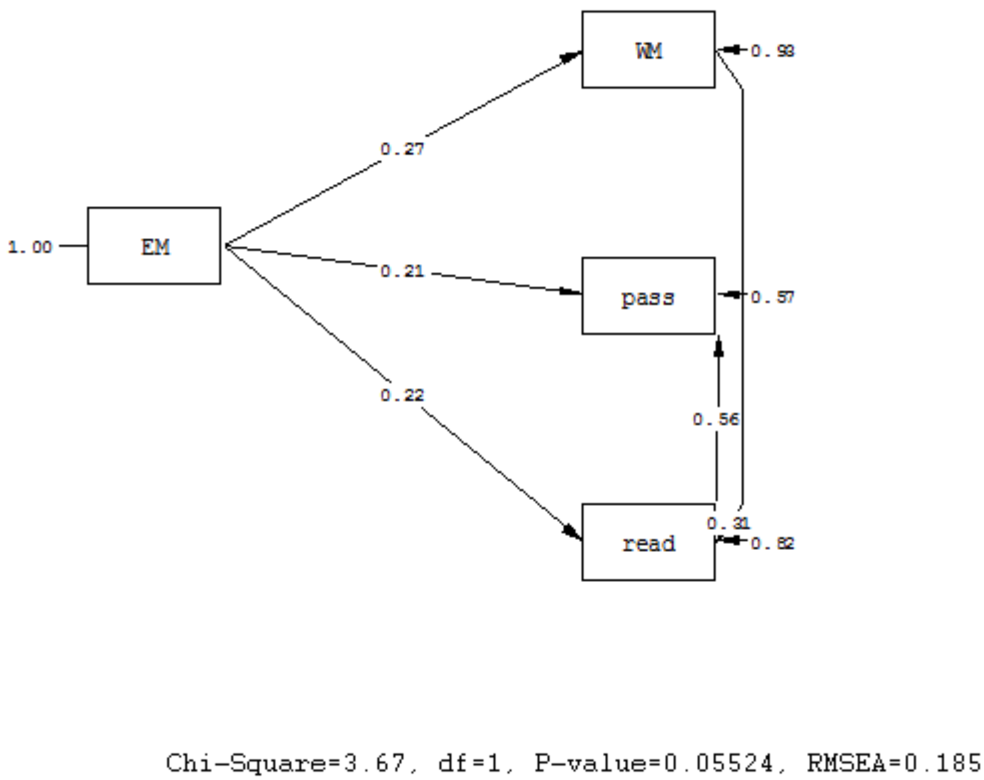


Figure 9: Posthoc path model for composite EM and working memory on reading achievement at age 9. Note: EM is episodic memory, WM is working memory, pass is passage comprehension, and read is reading fluency.

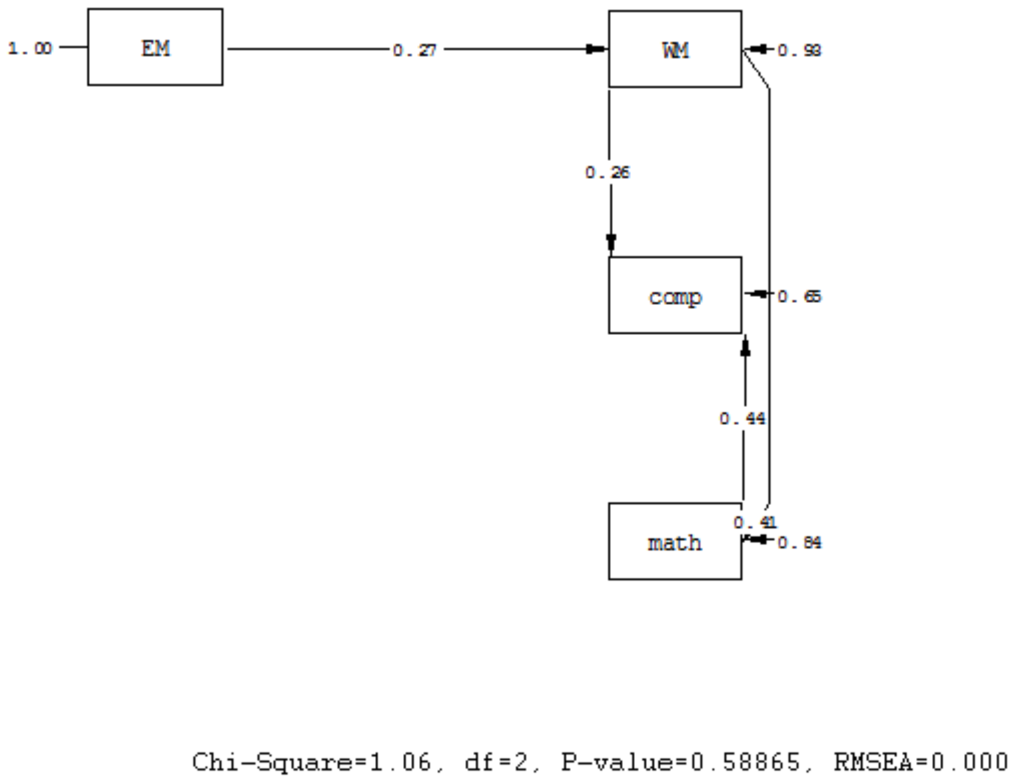


Figure 10: Posthoc path model for composite EM and working memory on math achievement at age 9. Note: EM is episodic memory, WM is working memory, comp is calculation, and math is math fluency.