Published in final edited form as:

Cogn Dev. 2018 ; 45: 141–151. doi:10.1016/j.cogdev.2017.07.002.

Behavioral Performance and Neural Areas Associated with Memory Processes Contribute to Math and Reading Achievement in 6-year-old Children

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Abstract

Associations between working memory and academic achievement (math and reading) are well documented. Surprisingly, little is known of the contributions of episodic memory, segmented into temporal memory (recollection proxy) and item recognition (familiarity proxy), to academic achievement. This is the first study to observe these associations in typically developing 6-year old children. Overlap in neural correlates exists between working memory, episodic memory, and math and reading achievement. We attempted to tease apart the neural contributions of working memory, temporal memory, and item recognition to math and reading achievement. Results suggest that working memory and temporal memory, but not item recognition, are important contributors to both math and reading achievement, and that EEG power during a working memory task contributes to performance on tests of academic achievement.

Keywords

working memory; episodic memory; math; reading; academic achievement; EEG

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1. Introduction

Observed variability in academic achievement has led to research on the contributions of various cognitive processes to academic success (e.g., St. Clair-Thompson & Gathercole, 2006). Our current understanding of the connection between memory and academic skills, however, is lacking because of the literature's focus on one type of memory (i.e., working memory), rather than the multiple systems that comprise complex memory events. Academic achievement requires coordination between multiple complex cognitive systems (e.g. Bryce, Whitebread, & Szucs, 2015). Therefore, it is unlikely that one component of memory can solely explain the contribution of memory to academic achievement. The purpose of our study was to examine the contributions of various memory types (working memory, temporal memory, and item recognition) to performance on standardized measures of academic achievement in 6-year-old children. In order to gain further evidence for the importance of memory systems for academic achievement, we examined both behavioral and neural indices of working and episodic memory (EM). Our study expands on previous research by encompassing multiple components of memory at both behavioral and neural levels.

Working memory (WM) has been a central focus in the academic achievement literature. Many studies have examined the contribution of WM and WM systems on academic success (e.g., Bull, Espy, & Wiebe, 2008; Nation, Adams, Bowyer-Crane, & Snowling, 1999; Passolunghi, Caviola, De Angostini, Perin, & Mammarella, 2016). WM requires updating and maintenance of active information and has been found to contribute to reading achievement in children (Siegel, 1994). WM allows for conceptualization and maintenance of words needed for comprehension (Baddeley, 2003; Siegel, 1994), and speed of reading comprehension (i.e. fluency; Ellis, 1996). Clearly, WM is an important factor in reading achievement. In addition to an association with reading achievement, WM has been connected to mathematics achievement (i.e. Lee & Bull, 2016). WM is needed for retrieval of numerical facts (Kaufman, 2002), maintenance and updating of numerical representations and strategy (Geary, 1993; Bull & Lee, 2014).

One of the components of the WM model is the Episodic Buffer (EB; Baddeley, 2000). The EB is believed to aid in the process of sending and receiving information from EM (Baddeley, 2000). In a study examining classic components of WM (i.e., EB, visuospatial sketchpad, phonological loop, and central executive), the EB was reported to contribute to reading achievement (Nevo & Breznitz, 2011). This finding suggests that the EB contributes to academic achievement independent of the other components of WM. Recall that EB sends and retrieves information from EM; therefore, it is likely that EM is involved in academic achievement as well. In fact, emerging evidence suggests that the recollection component of EM contributes to some aspects of academic achievement over and above WM (Blankenship, O'Neill, Ross, & Bell, 2015). However, no study has considered both temporal memory (recollection proxy) and item recognition (familiarity proxy) measures when examining the relation between EM and academic achievement. We propose that EM plays an independent role in academic achievement.

As previously noted, EM may be divided into two components, recollection and familiarity (Yonelinas, 2002). Recollection allows for vivid re-experience of an event and its context during retrieval, whereas familiarity refers to a general sense of knowing that an event has occurred (Ghetti & Lee, 2013; Yonelinas, 2002). Given the characteristics of recollection and familiarity, tasks requiring retrieval of contextual information (e.g., temporal memory) are typically used as a proxy of recollection, while tasks excluding contextual retrieval (e.g., item recognition) are typically used as a proxy of familiarity (e.g., Yonelinas, 2002). While temporal memory and item recognition are more likely to elicit recollection and familiarity, respectively, these are not process pure measures of these constructs. In terms of development, children show improvements in recollection performance throughout middle childhood and into adolescence. Familiarity performance, however, stabilizes earlier, around age 8 (Ghetti & Angelini, 2008). There has been little research examining how the EM processes of recollection and familiarity are related to academic achievement in typically developing children. Mirandola and colleagues (2011) examined recollection and familiarity in adolescents with and without reading difficulties. They found that the adolescents with reading difficulties displayed a deficit in recollection but not familiarity when compared to typical reading controls. These researchers did not consider other critical contributors to academic achievement, such as WM and intelligence (IQ). Additionally, they did not consider how recollection and familiarity relate to typical reading development. Other researchers have reported connections between recollection and academic achievement during middle childhood in typically developing children (Blankenship et al., 2015); however, no work has considered neural contributions of EM or familiarity.

Associations between recollection and math are rarely examined, but may be found indirectly through recall tasks (Stevenson & Newman, 1986). Yonelinas (2002) proposed that recall tasks elicit recollection more so than familiarity processes, especially if recall of contextual information is required (e.g., temporal memory; Yonelinas, 1994). This suggests that recognition is more reliant on familiarity, and recall is more reliant on recollection. No studies thus far have directly compared recollection and familiarity to math achievement. It is likely that recollection would contribute to math because of the effortful reliance on recall during mathematical calculations and problem solving. For example, when completing a math problem, retrieval of key facts and procedures related to solving the problem must be recalled in order to be successful. This recall process would likely rely on recollection processes, especially in young children who are just developing mathematical processes.

Many of the neural processes observed during math and reading performance are similar to those associated with WM and EM. As such, the frontal lobe activation observed during math (e.g., calculation) and reading (e.g., reading fluency) tasks is typically attributed to WM (e.g., King & Kutas, 1995; Metcalfe, Ashkenazi, Rosenberg-Lee, & Menon, 2013; Turkeltaub, et al., 2003). In terms of EEG activity, alpha oscillations are typically correlated with WM performance in adults (Klimesch, 1999) and children (Wolfe & Bell, 2004). Similarly, temporal lobe activation during math and reading has been suggested to reflect explicit memory systems, which includes EM (Tulving, 2002; Tulving, 1972; Turkeltaub et al., 2003). With respect to oscillations, theta band activity is typically associated with EM in adults (Klimesch et al, 2001) and children (Blankenship & Bell, 2015). In academic achievement research, focus is often placed on another type of explicit memory, specifically

semantic memory. Semantic memory differs from EM in that it does not involve contextual information, but rather factual information void of its context (Tulving, 1972). Factual information is key for being successful academically, but contextual information associated with EM is likely critical for acquiring math and reading abilities.

In order to fully understand how academic achievement operates, a comprehensive view of memory is necessary. We took this approach by examining the unique contributions of WM and the EM processes of item recognition and temporal memory to reading and math achievement, while controlling for the contributions of IQ. The contributions of WM and EM were considered at both behavioral and neural levels. Recollection and familiarity are related, but distinct EM processes. Understanding how memory relates to academic achievement behaviorally and neutrally may provide stronger evidence for the importance of various memory processes for academic achievement.

In sum, we examined the contributions of three memory processes to academic achievement in typically developing children. We focused on these processes in 6-year-old children because by age 6 most children have finished their first formal year of education, and thus will have had exposure to testing situations similar to the assessments given in our study. That being said, the constructs of interest tend to display continuity throughout middle childhood, so similar results may be found throughout this period. Furthermore, middle childhood is associated with increases in WM ability as well as improvements in use of encoding strategies, and thus EM performance (for review see Schneider & Ornstein, 2015). Both academic exposure and EM ability makes middle childhood an important period of development to study associations between memory and academic performance. We hypothesized that our measure of temporal memory (i.e., a proxy for recollection) would statistically predict reading and math achievement, as assessed by standardized tests, over and above WM. We did not expect our measure of item recognition (i.e., a proxy for familiarity) to contribute to performance on standardized reading and math tests. Additionally, we examined the electrophysiological neural correlates (via electroencephalogram; EEG) of WM, temporal memory, and item recognition in relation to academic achievement. EEG analyses were included to provide converging evidence of the impact of WM, temporal memory, and item recognition to academic achievement. We hypothesized that electrophysiology during both WM (i.e., frontal activation) and temporal memory (i.e., temporal activation) tasks would contribute to all measures of math and reading achievement. Similar to our behavioral hypothesis, we did not expect electrophysiology during the item recognition task to contribute to math or reading achievement.

2. Method

2.1. Participants

Participants included 242 children who were 6 years old ($M = 6.64$, $SD = 0.44$; 50% boys). The majority of children were in 1st grade (65.4%) or kindergarten (24.2%); 10% of children were in 2nd grade; and one child was in 3rd grade. Children were two cohorts (approximately 75% of the participants) of a larger longitudinal study focused on individual differences in the development of cognition and emotion. The remaining 25% of the larger

longitudinal study comprised of a third cohort and did not have a research visit at age 6. Most of the children were initially recruited as infants and had been in the research lab for several previous visits across infancy and early childhood. Half of one cohort, however, were newly recruited for this 6-year lab visit. The two cohorts were recruited by two research locations. Of the 242 children, 102 (54 long-term participants, 48 newly recruited) were seen at the XX location, while the remaining 140 children (all long-term participants) were seen at the YY location. (The third cohort of children who did not have a research visit at age 6 were associated with the XX location.) The children were primarily Caucasian (78%), with 14% identifying as African American, 7% as multi-racial, and 1% as Asian. The children's parents came from diverse educational backgrounds. For fathers, 8.3% did not complete high school, 15.15.3% high school graduates, 22.8% 2-year college, and 53.6% beyond 2-years of college. Regarding mothers, 2.5% did not complete high school, 7.63% high school graduates, 24.5% 2-year college, and 65.4% beyond 2-years of college.

2.2 Procedures

Data were collected at both research locations using identical protocols. Research assistants from each location were trained together by the project's Principal Investigator (the 4th author) on protocol administration, as well as on behavioral and electrophysiological data collection and coding. To ensure that identical protocol administration was maintained between the labs, the XX site periodically viewed DVD recordings and electrophysiology files collected by the YY lab. To ensure that identical coding criteria were maintained between labs, the XX lab provided reliability coding for behavioral data and verification of artifact screening and data editing for electrophysiology data collected and coded by the YY lab.

Upon arrival at the research laboratory, a research assistant who explained the study procedures and obtained verbal greeted children and sign consent from the child and signed consent from the mother. After a brief warm-up period, children were fitted with the EEG cap and participated in a variety of behavioral tasks assessing cognitive and emotional development. The session video feed was digitally recorded for later behavioral coding. As compensation for participation, parents received a \$50 gift card and children received a small gift and a \$10 gift card.

2.3. Electrophysiology

EEG data were collected during both the EM (retrieval) and WM tasks, as well as during a one minute eyes closed baseline. Recordings were made from 16 left and right scalp sites [frontal pole (Fp1, Fp2), frontal (F3, F4, F7, F8), central (C3, C4), temporal (T7, T8), parietal (P3, P4, P7, P8), and 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 K Ω .

The electrical activity from each lead was amplified using separate James Long Company Bioamps (James Long Company; Caroga Lake, NY). During data collection, the high pass filter was a single pole RC filter with a 0.1 Hz cut-off (3 dB or half-power point) and 6 dB per octave roll-off. The low pass filter was a two-pole Butterworth type with a 100 Hz cut-off (3 dB or half-power point) and 12 dB octave roll-off. 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. The acquisition software used was Snapshot-Snapstream (HEM Data Corp., Southfield, MI) and the raw data were stored for later analyses.

Prior to the recording of each participant a 10 Hz, 50 uV peak-to-peak sine wave was input through each amplifier. This calibration signal was digitized for 30 seconds and stored for subsequent analysis. To ensure that the EEG data being collected were as clean as possible, a visual inspection of the incoming data from each electrode was performed by a trained experimenter viewing the data on a computer in a control room adjacent to the testing room. This experimenter also viewed the testing session via camera and inserted event marks in the EEG data at the start and finish of the tasks while the data were being collected. These event marks were later used to segment the task portions from the ongoing EEG record for data 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 100 μ V or greater. Gross motor movements over 200 μ V 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. EEG power was computed for the alpha 8–13 Hz and theta 4–7 Hz bands. Power was expressed as mean square microvolts and data was transformed using the natural log (ln) to normalize the distribution. We focused on alpha and theta as these bands have been linked to WM and EM, respectively (Klimesch, 1999; Nyhus & Curran, 2010). Power was examined in frontal (F3, F4, F7, F8) and temporal regions (T7, T8). EEG power was examined during the retrieval conditions of the EM task. Retrieval EEG was collected during the presentation of each individual question and aggregated based on question type (i.e., temporal memory and item recognition). Average EEG collection time was 43.79 (SD = 15.45) seconds for temporal memory, and 36.76 (SD = 12.64) seconds for item recognition. WM EEG was collected during each digit presentation and subsequent retrieval, and most common digit span length (2 digits) power was used in the analyses. Average EEG collection time was 12.34 (SD = 4.71) seconds for the WM task.

2.3. Episodic Memory Task

An adaptation of the Corsi-Milner (Milner et al., 1991) recognition memory task was used to examine temporal memory (recollection proxy) and item recognition (familiarity proxy). The original task was developed to examine the ability to make serial ordered judgments with frontal lobe impairments and utilized abstract paintings on index cards. For our task, the children viewed simple color photographs of everyday objects (e.g., ice cream cone) and

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were instructed to make both item memory (i.e., item recognition; “Which item did you see before?”) and temporal memory (i.e., temporal memory; “Which item did you see last?”) judgments. To begin, two simple color drawings were presented on a computer screen, followed by the presentation of one practice temporal memory and one item recognition question. 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 also a question that was read aloud by the experimenter. Sometimes the question asked the children to indicate which image they had seen before (item recognition) and other times the question asked which picture they had seen last (temporal memory). For the item recognition questions, one image had been presented previously and the other was new. For the temporal memory questions, both images had been presented previously. These questions were based on the literature suggesting recency judgments elicit recollection more strongly than familiarity (e.g., Brown & Aggelton, 2001). There were a total of 10 questions (5 “seen before”, 5 “seen last”) and each participant received the same task presentation. There were no restrictions in sampling for the questions (i.e., samples did not have to be part of the immediately preceding subset). The variable of interest was total correct within each EM condition (i.e., temporal memory and item recognition).

2.4. Working Memory Task

A backwards digit span (BDS) task was administered to assess WM. Children were initially presented with two digits and instructed to 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.

2.5. Assessments of Math and Reading

Woodcock Johnson (WJ) III Tests of Achievement were used to measure math and reading ability (Woodcock, McGrew, Mather, & Schrank, 2001). Measures of math achievement included the calculation and math fluency subtests. Measures of reading achievement included the passage comprehension and reading fluency subtests. The variables of interest were age equivalence within each measure. The WJ III subtests demonstrate high reliabilities of .80 or higher (Nelson, Brenner, Lane, & Smith, 2004).

2.6. Verbal IQ

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The Peabody Picture Vocabulary Test IV (PPVT; Dunn & Dunn, 2007) was administered as a proxy for verbal IQ. Because intelligence is typically correlated with EM, WM, and reading and math performance, we controlled for this variable in our analyses. The PPVT is a nationally standardized instrument, and the measure of interest was participants’ standardized scores.

3. Results

3.1. Correlations

For descriptive statistics and correlations refer to Table 1. Briefly, children reproduced an average of 3.02 (SD = .82) digits on the WM task (i.e., BDS). Performance on the item recognition task (proportion correct; $M = .86$; $SD = .21$) differed from performance on the temporal memory task (proportion correct; $M = .65$, $SD = .25$), $t(235) = 9.26$, $p < .01$ with children performing better on item recognition when compared to temporal memory. Of the 242 children, 57 were unable to complete the reading fluency subtest due to reading level, 4 did not complete the passage comprehension subtest, 5 were unable to complete the calculation subtest, and 3 did not complete the math fluency subtest. All WJ III measures (reading fluency, math fluency, reading comprehension, calculation) were positively correlated with WM, temporal memory, and each other. Only reading comprehension was correlated with item recognition. Hierarchical regressions were used to examine the contributions of memory to the individual reading and math performance measures.

For the regressions focused on behavioral predictors of math and reading performance, verbal IQ (i.e., PPVT) and WM task score were entered into the first step of each equation. We entered verbal IQ and WM into the first step because they are well known contributors to academic achievement. Item recognition and temporal memory scores for the EM task were entered into the second step of each equation.

For the regressions focused on the neural predictors of math and reading performance, verbal IQ was again entered into the first step of each equation as was baseline EEG. The electrode sites and frequency band varied depending on task analyzed (e.g., F3, F4, F7, F8, and alpha for WM task; T7, T8, and theta for EM task). Composite (F3, F4, F7, and F8) frontal scores were used for both baseline and WM EEG power, and composite temporal scores were used for both baseline and retrieval (item recognition and temporal memory) power (T7 and T8). Corresponding electrode sites during the WM, temporal memory, or item recognition task were entered into the second step of the equations.

3.2. Behavioral Results for Reading and Math Achievement

3.2.1. Passage comprehension—Verbal IQ and WM in Step 1 accounted for 18% of the variance in passage comprehension. The variables in Step 2 accounted for an additional 4% of the variance in math fluency, with verbal IQ (3%), WM (9%), temporal memory (2%), and item recognition (2%), contributing unique variance (see Table 2a).

3.2.2. Reading fluency—Verbal IQ and WM in Step 1 accounted for 10% of the variance in reading fluency. The variables in Step 2 accounted for an additional 4% of the variance in reading fluency, with verbal IQ (3%), WM (2%), and temporal memory (3%), but not item recognition, contributing unique variance (see Table 2b).

3.2.3. Calculation—Verbal IQ and WM in Step 1 accounted for 15% of the variance in calculation. The variables in Step 2 accounted for an additional 3% of the variance in calculation, with WM (8%) and temporal memory (3%), but not for verbal IQ or item recognition, contributing unique variance (see Table 2c).

3.2.4. Math fluency—Verbal IQ and WM in Step 1 accounted for 16% of the variance in math fluency. The variables in Step 2 accounted for an additional 3% of the variance in math fluency, with WM (10%) and temporal memory (3%), but not for verbal IQ or item recognition, contributing unique variance (see Table 2d).

3.3. WM EEG Results for Reading and Math Achievement

EEG alpha power in frontal regions during the WM task was used in the statistical prediction of each math and reading measure. As noted, EEG alpha has been associated with WM (Klimesch, 1999). Verbal IQ and eyes closed baseline EEG were controlled in each equation.

3.3.1. Passage comprehension—Verbal IQ and baseline frontal power accounted for 8% of the variance in passage comprehension performance. The variables in Step 2 accounted for an additional 2% of the variance, with verbal IQ and WM frontal power contributing unique variance (see Table 3a).

3.3.2. Reading fluency—Verbal IQ and baseline frontal power accounted for 8% of the variance in reading fluency performance. The variables in Step 2 did not account for additional variance (see Table 3b).

3.3.3. Calculation—Verbal IQ and baseline frontal power accounted for 6% of the variance in calculation performance. The variables in Step 2 accounted for an additional 2% of the variance, with verbal IQ and WM frontal power contributing unique variance (see Table 3c).

3.3.4. Math fluency—Verbal IQ and baseline frontal power accounted for 5% of the variance in math fluency performance. The variables in Step 2 did not account for an additional 2% of variance, with verbal IQ and WM frontal power contributing unique variance (see Table 3d).

3.4. Temporal Memory and Item Recognition EEG Results for Reading and Math Achievement

EEG theta power in temporal regions during the temporal memory and item recognition EM task was used in the statistical prediction of each math and reading measure. As noted, EEG theta has been associated with EM (Nyhus & Curran, 2010). Verbal IQ and baseline EEG were controlled in each equation. Temporal power during retrieval for the temporal memory and item recognition conditions of the EM task did not contribute unique variance to any of the academic achievement measures (see Tables 4 and 5).

4. Discussion

We examined both behavioral and neural contributions to measures of academic achievement (math and reading). Findings suggest that both temporal memory (recollection proxy) and WM, but not item recognition (familiarity proxy), contribute to math and reading performance, after controlling for the contributions of verbal IQ. These results are consistent with past research separately examining contributions of WM (e.g., Alloway & Alloway, 2010; Swanson, 1994; St. Clair-Thompson & Gathercole, 2006) and the sole study

examining both recollection and familiarity (Mirandola et al., 2011) to academic achievement. Our study is the first, however, to examine temporal memory (recollection proxy), item recognition (familiarity proxy) and WM simultaneously. Additionally, our study is the first to examine possible contributions of the neural correlates of WM, temporal memory, and item recognition performance with math and reading achievement. Our results suggest that alpha neural activity within frontal regions during WM tasks is associated with performance on academic achievement tests.

EM was segmented into temporal memory and item recognition in our study. Behavioral results suggest that temporal memory, but not item recognition, contributes to all measures of math and reading achievement, over and above WM. Our measures of temporal memory and item recognition were designed to tap into recollection and familiarity, respectively. A recent study found that adolescents with poor reading comprehension skills demonstrate poorer recollection when compared with average comprehenders (Mirandola et al., 2011). This same study suggested that familiarity ability remained intact. Reading requires retrieval of detailed information in order to comprehend past and current reading material, and to make connections between. Additionally, in order to understand a complex passage, children need to retrieve the meanings of words. Yonelinas (2002) suggests that semantic processing (e.g., word retrieval) requires recollection-based processes. These results coupled with past research and theory suggests that recollection is an important of reading achievement.

The children in our study showed associations between temporal memory and math fluency and calculation. To our knowledge, no studies exist examining the contributions of recollection and familiarity to performance on standardized tests of math achievement. However, the relation between recollection and math has been found indirectly through the use of recall tasks (Stevenson & Newman, 1986), but again this was not the primary focus of previous research and thus the researchers did not control for WM or IQ, nor did they include measures of familiarity. Our study suggests that temporal memory is an important contributor to academic achievement over and above verbal IQ and uniquely from WM. The relation between temporal memory and math ability is likely explained due reliance on recall abilities during mathematical procedures. Specifically, when solving math problems it is important to recall the rules associated with the type of problems being solved.

Performance on the item recognition task contributed to reading comprehension, but not to the other measures of reading and math. This finding was unexpected, since we were not anticipating item recognition to contribute to achievement measures. Further, item recognition only contributed to one measure of achievement. This suggests that item recognition is not as crucial as temporal memory for most academic achievement measures. Further supporting this assumption, recognition tasks (reliant on familiarity) do not tap into representations that are necessary to assess prior knowledge (Long, Prat, Johns, Morris, & Jonathan, 2008). Yonelinas (2002) suggested that familiarity might be useful in novel learning situations, but only under certain conditions. This leads to an alternative explanation; the tasks we used to measure academic achievement tapped into temporal memory more so than item recognition. Most of our academic measures required recall, retrieving information without the information itself being present. Recall tasks are more likely to result in retrieval of contextual details (e.g., temporal order), thus eliciting

recollection-based processes more so than familiarity (Yonelinas et al., 2002). Future studies should examine the relation between temporal memory and item recognition to academic achievement using non-recall tasks.

Frontal EEG power during the WM task was negatively correlated with the WM task, calculation, math fluency, and reading comprehension. This negative association was not hypothesized, but is in line with past research (Klimesch 1999). Alpha power decreases during working memory tasks (e.g., Sauseng, Klimesch, Schabus, & Doppelmayr), therefore, the negative association between frontal EEG power, within the alpha band, and performance on cognitive tasks would be expected. Frontal EEG power during baseline and the WM task contributed to academic achievement. These results varied depending on the task, with both baseline and task EEG relating to calculation and only WM EEG relating to math fluency and reading comprehension. Power during the retrieval portion of the EM temporal memory and item recognition tasks did not contribute to any of the measure of academic achievement. These results partially supported our hypothesis that EEG during WM and temporal memory, but not item recognition, would contribute to academic achievement. However, it was expected that frontal and temporal EEG would contribute to all academic achievement measures given that both frontal and temporal regions have been associated with math and reading performance (e.g., Turkeltaub et al., 2003). It is possible that the lack of association between frontal WM EEG and reading fluency was a result of the difficulty of the task. Many children ($n = 57$) were unable to complete the reading fluency assessment, which may have impacted our results. Another explanation is that the underlying neural processes associated with WM and reading fluency differ when compared to other academic measures. In sum, further research is needed to determine the neural overlap between WM and academic achievement.

EM EEG power was not correlated to any of the behavioral measures. Temporal EEG power during EM temporal memory and item recognition retrieval performance did not contribute to any measures of achievement. We expected temporal EEG power during temporal memory to contribute to all measures of academic achievement, however, we collected EEG during the WM and EM tasks, which may have affected our results. EEG was collected during WM and EM temporal memory, in order to make indirect connections between these tasks and academic achievement. Future studies should also collect EEG during achievement assessments in order to make direct comparisons. We did not do so because the children wore the EEG cap for approximately 90 minutes during the cognition and emotion portions of our larger study. Having them also wear the EEG cap during standardized achievement testing would have been too demanding of young children.

There were some limitations to this work. First, we examined both temporal memory and item recognition within the theta band given that EM is often associated with theta (e.g., Klimesch, 1999), and both of these construct are linked with EM. There is research, however, suggesting gamma activation is related to familiarity, while theta is related to recollection (Gruber, Tsivilis, Giabbiconi, & Muller, 2008). Future studies should examine additional bands when relating familiarity EEG activity to academic achievement. Because our data were collected within the context of a larger longitudinal study, we were restricted to one presentation of each type of memory task. Second, we only collected EEG during the

WM and EM tasks. As mentioned previously, collecting EEG during the achievement tests may allow for better understanding of the neural correlates associated, and allow for comparisons between WM, temporal memory, and item recognition. Third, we were interested in examining the neural correlates of WM, temporal memory, and item recognition in relation to academic achievement; however, only the behavioral measure of WM related to the neural regions hypothesized (i.e., frontal scalp locations, EEG alpha band). We examined temporal scalp locations using the EEG theta band during both the temporal memory and item recognition measures of the EM task because of existing literature (e.g., Yonelinas et al., 2002). Our EM measures, however, were not correlated with the neural regions hypothesized. The lack of correlation between temporal memory, item recognition, and neural activity may explain why we did not find a connection between temporal activation during the retrieval portion of the EM task and academic achievement. Additionally, due to the low number of trials (10) we were unable to examine EEG theta power for correct versus incorrect trials during temporal memory or item recognition performance. Past research has shown that theta is associated with correct recognition performance (see Hsieh & Ranganath, 2014 for review). Our study should be replicated using a larger number of trials. Finally, children performed well on our item recognition measure (60% receiving a perfect score). Children tend to perform significantly better on tasks tapping familiarity compared to tasks tapping recollection (Holliday, 2003). In fact, it has been argued that familiarity performance stabilizes at a much younger age than recollection performance (Ghetti & Angelini, 2008). Additional research on the developmental trajectories of familiarity vs. recollection would provide insight on our results.

Overall, our study demonstrated that temporal memory and WM, but not item recognition, contribute unique variance to math and reading performance, even after controlling for verbal IQ. Additionally, our study provides evidence for neural contributions of WM to academic achievement. Such results may inform educational policies and academic achievement interventions. Specifically, instruction and evaluation may be designed in a way that taps recollection processes more so than familiarity. Furthermore, our results may provide insight into why interventions targeting WM are often not successful long term (e.g., Elliott, Gathercole, Alloway, Holmes, & Kirkwood, 2010). Perhaps additional processes need to be considered in addition to WM. In conclusion, both WM and recollection should be considered when examining academic achievement.

Acknowledgments

Blinded for review.

References

- Alloway TP, Alloway RG. Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*. 2010; 106:20–29. [PubMed: 20018296]
- Baddeley A. Working memory. *Science*. 1992; 255:556–559. [PubMed: 1736359]
- Baddeley A. The episodic buffer: a new component of working memory? *Trends in Cognitive Science*. 2000; 4:417–423.

- Baddeley A. Working memory and language: an overview. *Journal of Communication Disorders*. 2003; 36:189–208. [PubMed: 12742667]
- Blankenship TL, Bell MA. Frontal- temporal coherence and executive functions contribute to active and passive processing memory performance in middle childhood. *Developmental Neuropsychology*. 2015; 40:430–444. [PubMed: 27043829]
- Blankenship TL, O'Neill M, Ross A, Bell MA. Working memory and recollection contribute to academic achievement. *Learning and individual differences*. 2015; 43:164–169. [PubMed: 26644761]
- Brown MW, Aggleton JP. Recognition memory: what are the roles of the perirhinal cortex and hippocampus? *Nature Reviews Neuroscience*. 2001; 2(1):51–61. [PubMed: 11253359]
- Bryce D, Whitebread D, Sz cs D. The relationships among executive functions, metacognitive skills and educational achievement in 5 and 7 year-old children. *Metacognition and Learning*. 2015; 10:181–198.
- Bull R, Espy KA, Wiebe SA. Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental neuropsychology*. 2008; 33:205–228. [PubMed: 18473197]
- Bull R, Lee K. Executive functioning and mathematics achievement. *Child Development Perspectives*. 2014; 8(1):36–41.
- Dunn LM, Dunn DM. PPVT-4: Peabody picture vocabulary test. 2007 Pearson Assessments.
- Elliott JG, Gathercole SE, Alloway TP, Holmes J, Kirkwood H. An evaluation of a classroom-based intervention to help overcome working memory difficulties and improve long-term academic achievement. *Journal of Cognitive Education and Psychology*. 2010; 9:227–250.
- Ellis NC. Working memory in the acquisition of vocabulary and syntax: putting language in good order. *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*. 1996; 49:234–250.
- Geary AC. Mathematical disabilities: cognitive, neuropsychological, and genetic components. *Psychological Bulletin*. 1993; 114:345–362. [PubMed: 8416036]
- Ghetti S, Angelini L. The development of recollection and familiarity in childhood and adolescence: evidence from the dual-process signal detection model. *Child Development*. 2008; 79:339–358. [PubMed: 18366427]
- Ghetti, S., Lee, IK. The development of recollection and familiarity during childhood. In: Bauer, PJ., Fivush, R., editors. *Handbook on the development of children's memory*. Vol. 1. Malden, MA: Wiley-Blackwell; 2013. p. 309–335.
- Holliday RE. Reducing misinformation effects in children with cognitive interviews: Dissociating recollection and familiarity. *Child development*. 2003; 74(3):728–751. [PubMed: 12795387]
- Hsieh LT, Ranganath C. Frontal midline theta oscillations during working memory maintenance and episodic encoding and retrieval. *Neuroimage*. 2014; 85:721–729. [PubMed: 23933041]
- Kaufmann L. More evidence for the role of the central executive in retrieving arithmetic facts- a case study of severe developmental dyscalculia. *Journal of Clinical and Experimental Neuropsychology*. 2002; 24:302–310. [PubMed: 11992213]
- King JW, Kutas M. Who did what and when? Using word-and clause-level ERPs to monitor working memory usage in reading. *Journal of cognitive neuroscience*. 1995; 7:376–395. [PubMed: 23961867]
- Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain research reviews*. 1999; 29:169–195. [PubMed: 10209231]
- Klimesch W, Doppelmayr M, Schimke H, Ripper B. Theta synchronization and alpha desynchronization in a memory task. *Psychophysiology*. 1997; 34:169–176. [PubMed: 9090266]
- Klimesch W, Doppelmayr M, Yonelinas A, Kroll NEA, Lazzara M, Rohm D, Gruber W. Theta synchronization during episodic retrieval: neural correlates of conscious awareness. *Cognitive Brain Research*. 2001; 12:33–38. [PubMed: 11489606]
- Long DL, Prat C, Johns C, Morris P, Jonathan E. The importance of knowledge in vivid text memory: An individual differences investigation of recollection and familiarity. *Psychonomic Bulletin & Review*. 2008; 15:604–609. [PubMed: 18567262]

- Metcalfe AW, Ashkenazi S, Rosenberg-Lee M, Menon V. Fractionating the neural correlates of individual working memory components underlying arithmetic problem solving skills in children. *Developmental cognitive neuroscience*. 2013; 6:162–175. [PubMed: 24212504]
- Milner B, Corsi P, Leonard G. Frontal-lobe contribution to recency judgments. *Neuropsychologia*. 1991; 29:601–618. [PubMed: 1944864]
- Mirandola C, Del Prete F, Ghetti S, Cornoldi C. Recollection but not familiarity differentiates memory for text in students with and without learning difficulties. *Learning and Individual Differences*. 2011; 21:206–209.
- Nation K, Adams JW, Bowyer-Crane CA, Snowling MJ. Working memory deficits in poor comprehenders reflect underlying language impairments. *Journal of experimental child psychology*. 1999; 73:139–158. [PubMed: 10328862]
- Nelson JR, Benner GJ, Lane K, Smith BW. Academic achievement of K-12 students with emotional and behavioral disorders. *Exceptional Children*. 2004; 71(1):59–73.
- Nevo E, Breznitz Z. Assessment of working memory components at 6 years of age as predictors of reading achievements a year later. *Journal of Experimental Child Psychology*. 2010; 109:73–90. [PubMed: 21115182]
- Nyhus E, Curran T. Functional role of gamma and theta oscillations in episodic memory. *Neuroscience & Biobehavioral Reviews*. 2010; 34:1023–1035. [PubMed: 20060015]
- Passolunghi MC, Caviola S, De Agostini R, Perin C, Mammarella IC. Mathematics Anxiety, Working Memory, and Mathematics Performance in Secondary-School Children. *Frontiers in psychology*. 2016; 7:1–6. [PubMed: 26858668]
- Sauseng P, Klimesch W, Schabus M, Doppelmayr M. Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International Journal of Psychophysiology*. 2005; 57:97–103. [PubMed: 15967528]
- Schneider W, Ornstein PA. The Development of Children's Memory. *Child Development Perspectives*. 2015; 9:190–195.
- Siegel LS. Working memory and reading: a life-span perspective. *International Journal of Behavioral Development*. 1994; 17:109–124.
- St Clair-Thompson HL, Gathercole SE. Executive functions and achievements in school: shifting, updating, inhibition, and working memory. *The Quarterly Journal of Experimental Psychology*. 2006; 59:745–759. [PubMed: 16707360]
- Stevenson HW, Newman RS. Long-term prediction of achievement and attitudes in mathematics and reading. *Child Development*. 1986; 57:646–659. [PubMed: 3720396]
- Swanson HL. Short-term memory and working memory: do both contribute to our understanding of academic achievement in children and adults with learning disabilities? *Journal of Learning Disabilities*. 1994; 27:34–50. [PubMed: 8133185]
- Tulving, E. Episodic and semantic memory. In: Tulving, E., Donaldson, W., editors. *Organization of memory*. New York: Academic Press; 1972.
- Turkeltaub PE, Gareau L, Flowers DL, Zeffiro TA, Eden GF. Development of neural mechanisms for reading. *Nature neuroscience*. 2003; 6:767–773. [PubMed: 12754516]
- Wolfe CD, Bell MA. Working memory and inhibitory control in early childhood: contributions from physiology, temperament, and language. *Developmental Psychobiology*. 2004; 44:68–83. [PubMed: 14704991]
- Woodcock, RW., McGrew, KS., Mather, N., Schrank, F. Woodcock-Johnson III NU tests of achievement. Rolling Meadows, IL: Riverside Publishing; 2001.
- Yonelinas AP. Receiver-operating characteristics in recognition memory: evidence for a dual-process model. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1994; 20:1341–1354.
- Yonelinas AP. The nature of recollection and familiarity: a review of 30 years of research. *Journal of Memory and Language*. 2002; 46:441–517.
- Yonelinas AP, Kroll NEA, Quamme JR, Lazzara MM, Sauve MJ, Widaman KF, Knight RT. Effects of extensive temporal lobe damage or mild hypoxia on recollection and familiarity. *Nature Neuroscience*. 2002; 5:1236–1241. [PubMed: 12379865]

Highlights

- We examined memory processes and academic achievement.
- Working memory predicted all measures of academic achievement.
- Temporal memory predicted all measures of academic achievement.
- Electrophysiology during working memory contributed to academic achievement.

Table 1

Correlations and Descriptive Statistics

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. WM.	1												
2. Temporal Memory	.16*	1											
3. Item Recognition	.09	-.13*	1										
4. Verbal IQ	.28***	.18**	.07	1									
5. Reading Fluency	.25***	.25***	.10	.27***	1								
6. Calculation	.36***	.22***	.12	.26***	.52***	1							
7. Math Fluency	.39***	.25***	.06	.24***	.60***	.81***	1						
8. Passage Comp.	.39***	.21***	.16*	.30***	.83***	.64***	.64***	1					
9. F Baseline EEG	-.10	.10	.03	.00	-.09	-.11	-.10	-.08	1				
10. WM. EEG	-.16*	.00	-.05	-.11	-.15	-.21**	-.19**	-.19**	.68***	1			
11. T Baseline EEG	-.03	.12	.02	.14*	.00	-.10	-.07	-.05	.78***	.64***	1		
12. Temporal EEG	-.04	.07	.06	.12	.06	-.13	-.10	-.02	.57**	.61***	.80***	1	
13. Item EEG	-.03	.05	.03	.11	.08	-.10	-.10	-.01	.58***	.61***	.78***	.91***	1
M	3.02	.65	.86	112.76	7.44	7.19	6.80	7.14	3.46	2.95	3.52	3.22	3.21
SD	.82	.25	.21	12.14	1.06	.80	.91	1.04	.56	.53	.55	.35	.35
N	238	236	236	242	185	237	239	238	236	230	234	227	227

Note:

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

WM (i.e., working memory) and F (frontal) baseline EEG measures were from frontal (F3, F7, F4, F8) scalp locations and used alpha band power (8–13 Hz). T (temporal) baseline EEG, temporal (i.e., temporal memory), and item (i.e., item recognition) EEG measures were from temporal (T7, T8) scalp locations and used theta band power (4–7 Hz).

Hierarchical Regression Analyses of Memory Task Performance Predicting Academic Achievement, after Controlling for Verbal IQ

Table 2

	R	R ²	F	F	β	t	sr ²
<i>a. Reading Comprehension</i>							
<i>Step 1.</i>	.42	.18		24.69***			
Verbal IQ					.19	3.10	.03
Working Memory					.33	5.36	.10
<i>Step 2.</i>	.46	.22	.04	5.06**	15.32***		
Verbal IQ					.17	2.70***	.03
Working Memory					.31	4.94**	.09
Temporal Memory					.16	2.56*	.02
Item Recognition					.14	2.27*	.02
<i>b. Reading Fluency</i>							
<i>Step 1.</i>	.32	.10		10.31***			
Verbal IQ					.22	2.99**	.05
Working Memory					.20	2.69**	.04
<i>Step 2.</i>	.37	.14	.04	3.69*	7.16***		
Verbal IQ					.18	2.70*	.03
Working Memory					.16	2.22*	.02
Temporal Memory					.19	2.58*	.03
Item Recognition					.10	1.36	.01
<i>c. Calculation</i>							
<i>Step 1.</i>	.38	.14		19.40***			
Verbal IQ					.15	2.29*	.02
Working Memory					.32	5.07***	.10
<i>Step 2.</i>	.42	.16	.02	3.93*	11.92***		
Verbal IQ					.12	1.87	.01

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	R	R ²	F	β	t	sr ²
Working Memory				.29	4.66***	.08
Temporal Memory				.17	2.69**	.03
Item Recognition				.07	1.19	.01
<i>d. Math Fluency</i>						
Step 1.	.40	.16	21.72***			
Verbal IQ				.12	1.93	.01
Working Memory				.35	5.65***	.12
Step 2.	.44	.19	4.08*	13.19***		
Verbal IQ				.09	1.49	.01
Working Memory				.33	5.25***	.10
Temporal Memory				.18	2.85**	.03
Item Recognition				.02	.40	.00

Note:

- *** p .001
- ** p .01
- * p .05.

The p-values for the final step of the regressions were < .001 for all measures of academic achievement.

Hierarchical Regression Analyses of Working Memory Task-related EEG (8–13 Hz) Predicting Academic Achievement, after Controlling for Verbal IQ and Baseline EEG

Table 3

	R	R ²	R ²	F	F	β	t	sr ²
<i>a. Reading Comprehension</i>								
<i>Step 1.</i>	.28	.08		9.73	***			
Verbal IQ						.27	4.20	.07
F Baseline EEG						-.08	-1.29	.01
<i>Step 2.</i>	.32	.10	.02	5.24	* 8.36	***		
Verbal IQ						.25	3.88	.06
F Baseline EEG						.06	.63	.00
WM EEG						-.20	-2.29	.02
<i>b. Reading Fluency</i>								
<i>Step 1.</i>	.27	.08		7.10	***			
Verbal IQ						.26	3.60	.07
F Baseline EEG						-.10	-1.40	.01
<i>Step 2.</i>	.29	.09	.01	1.95	5.41	***		
Verbal IQ						.26	3.49	.06
F Baseline EEG						-.03	-.34	.00
WM EEG						-.12	-1.40	.01
<i>c. Calculation</i>								
<i>Step 1.</i>	.25	.06		7.42	***			
Verbal IQ						.21	3.21	.04
F Baseline EEG						-.13	-2.05	.02
<i>Step 2.</i>	.28	.08	.02	3.80	* 6.28	***		
Verbal IQ						.19	2.61	.04
F Baseline EEG						-.02	-.17	.00
WM EEG						-.17	-1.95	.02

	R	R ²	R ²	F	F	β	t	st ²
<i>d. Math Fluency</i>								
<i>Step 1.</i>	.22	.05		5.77**				
Verbal IQ						.20	2.96**	.04
F Baseline EEG						-.10	-1.49	.01
<i>Step 2.</i>	.26	.07	.02	4.08*	5.26**			
Verbal IQ						.18	2.70**	.03
F Baseline EEG						.02	.24	.00
WM EEG						-.18	-2.02*	.02

Note:

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

WM = working memory. The p-values for the final step of the regressions were < .001, .001, < .001, and .002 for reading comprehension, reading fluency, calculation, and math fluency, respectively. EEG within frontal regions (F3, F4, F7, F8) and within the alpha (

Hierarchical Regression Analyses of Temporal Memory Task-related EEG (4–7 Hz) Predicting Academic Achievement, after Controlling for Verbal IQ and Baseline EEG

Table 4

	R	R²	F	F	β	t	sr²
a. Reading Comprehension							
<i>Step 1.</i>	.28	.07		9.20 ***			
Verbal IQ					.28	4.24 ***	.08
T Baseline EEG					-.08	-1.28	.01
<i>Step 2.</i>	.28	.07	.00	.03	6.11 ***		
Verbal IQ					.28	4.23 ***	.08
T Baseline EEG					-.10	-.90	.00
Temporal Memory EEG					.02	.16	.00
b. Reading Fluency							
<i>Step 1.</i>	.26	.07		6.21 **			
Verbal IQ					.27	3.52 ***	.07
T Baseline EEG					-.06	-.80	.00
<i>Step 2.</i>	.27	.07	.00	1.00	4.47 **		
Verbal IQ					.26	3.44 ***	.06
T Baseline EEG					-.15	-1.28	.01
Temporal Memory EEG					.12	1.00	.01
c. Calculation							
<i>Step 1.</i>	.27	.08		8.91 ***			
Verbal IQ					.26	3.98 ***	.07
T Baseline EEG					-.13	-1.99 **	.02
<i>Step 2.</i>	.29	.08	.00	2.03	6.64 ***		
Verbal IQ					.26	3.98 ***	.07
T Baseline EEG					-.01	-.07	.00
Temporal Memory EEG					-.15	-1.43	.01

	R	R ²	F	F	β	t	sr ²
<i>d. Math Fluency</i>							
<i>Step 1.</i>	.24	.06		6.65**			
Verbal IQ					.23	3.47***	.05
T Baseline EEG					-.11	-1.68*	.01
<i>Step 2.</i>	.25	.06	.00	1.21	4.84**		
Verbal IQ					.23	3.47***	.05
T Baseline EEG					-.02	-.14	.00
Temporal Memory EEG					-.12	-1.10	.01

Note:
*** p .001
** p .01
* p .05.

The p-values for the final step of the regressions were < .001, .005, < .001, and .003 for reading comprehension, reading fluency, calculation, and math fluency, respectively.

Hierarchical Regression Analyses of Item Recognition Task-related EEG (4–7 Hz) Predicting Academic Achievement, after Controlling for Verbal IQ and Baseline EEG

Table 5

	R	R ²	R ²	F	F	β	t	sr ²
<i>a. Reading Comprehension</i>								
<i>Step 1.</i>	.28	.07		9.20	***			
Verbal IQ						.28	4.24	.08
T Baseline EEG						-.08	-1.28	.01
<i>Step 2.</i>	.28	.07	.00	.22	6.18	***		
Verbal IQ						.28	4.24	.08
T Baseline EEG						-.12	-1.18	.01
Item Recognition EEG						.05	.47	.00
<i>b. Reading Fluency</i>								
<i>Step 1.</i>	.26	.07		6.21	**			
Verbal IQ						.27	3.52	.07
T Baseline EEG						-.06	-.80	.00
<i>Step 2.</i>	.28	.08	.01	1.73	4.73	**		
Verbal IQ						.26	3.44	.06
T Baseline EEG						-.17	-1.51	.01
Item Recognition EEG						.15	1.32	.01
<i>c. Calculation</i>								
<i>Step 1.</i>	.27	.08		8.91	***			
Verbal IQ						.26	3.98	.07
T Baseline EEG						-.13	-1.99	.02
<i>Step 2.</i>	.28	.08	.00	.56	6.11	***		
Verbal IQ						.26	3.96	.07
T Baseline EEG						-.07	-.68	.00
Item Recognition EEG						-.08	-.75	.00

	R	R ²	F	F	β	t	sr ²
<i>d. Math Fluency</i>							
<i>Step 1.</i>	.24	.06		6.65**			
Verbal IQ					.23	3.47***	.05
T Baseline EEG					-.11	-1.68*	.01
<i>Step 2.</i>	.25	.06	.82	4.70**			
Verbal IQ					.23	3.46***	.05
T Baseline EEG					-.04	-.37	.00
Item Recognition EEG					-.09	-.91	.00

Note:

p .001
**
p .01
*
p .05.

The p-values for the final step of the regressions were < .001, .003, < .001, and .001 for reading comprehension, reading fluency, calculation, and math fluency, respectively.