

Title: Age- and performance-related differences in source memory retrieval during early  
childhood: Insights from event-related potentials

Running title: Age- and performance-related differences in ERPs

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## Abstract

Across early childhood, children's ability to remember individual items and the details that accompany these items (i.e., episodic memory) improves greatly. Given that these behavioral improvements coincide with increases in age, effects of age and performance are often confounded. This study used event-related potentials (ERPs) to investigate age- and performance-related differences in the neural processes underlying the development of memory for details during early childhood. Using a source memory paradigm, ERP components related to episodic memory, the negative component (Nc) and late slow wave (LSW), were examined in 4- to 8-year-old children. Analyses focused on trials for which children correctly remembered the source related to an item versus trials where the item was remembered but the source was forgotten. Results revealed LSW, but not Nc, differed as a function of age and performance. Specifically, LSW effects were similar across source correct and source incorrect trials in all high-performing children and in low-performing older children; however, LSW effects differed across conditions in low-performing younger children. Results show developmental differences in retrieval processes across early childhood and highlight the importance of considering age and performance when examining electrophysiological correlates of episodic memory during development.

**Keywords:** early childhood; episodic memory development; age-related differences; individual differences; event-related potentials

## Introduction

The ability to recall details of past events allows us to build rich personal histories. Several prominent theories suggest that memories recalled with details are qualitatively different from memories that lack details and are supported by different mnemonic processes, namely familiarity and recollection (e.g., Tulving, 1972, 1993; for review see Yonelinas, 2002; Diana, Vilberg, & Reder, 2005). Briefly, familiarity occurs relatively automatically and is thought to support the retrieval of an item lacking detail. Recollection is slower, as it requires effortful retrieval of the contextual details surrounding an item and is often assessed via source memory tasks.

Evidence in support of the claim that memories with details are qualitatively different from those without details comes from electrophysiological research in adults and school-aged children, which have documented differences in brain activity when memories are recalled with contextual details (i.e., recollected) versus when memories are recalled without these details (recognized as familiar; for review in adults see, Rugg & Curran, 2007). For example, in one study (Wilding & Rugg, 1996), adults were asked to remember a list of words presented in either a female or male voice (the source of the information). During recall, event-related potentials (ERPs) were recorded, and results indicated that ERPs generated in response to old words differed from new words. Furthermore, results documented differences in ERPs to words recalled as old with correct details (i.e., the voice source) compared to words identified as old but for which this detail was forgotten (Wilding & Rugg, 1996). Specifically, old words recalled with accurate details showed greater ERP amplitudes at parietal electrodes compared to words identified as old but without accurate details. Because these effects were maximal over left parietal electrodes, this has often been referred to as a left parietal episodic memory (EM) effect.

From a developmental perspective, it is widely accepted that children's ability to recall detailed memories follows a protracted trajectory, with improvements occurring during early childhood between the ages of approximately 5 and 7 years (e.g., Drumme & Newcombe, 2002; Riggins, 2014; Riggins & Rollins, 2015). However, the neural correlates associated with these age-related improvements are not well understood. Additionally, recent studies examining age-related differences in memory in middle-childhood through late-adulthood have highlighted the importance of considering not only age-, but performance-, related differences in memory and its neural substrates, as age can be an imprecise measure of maturation due to individual differences (Duarte, Ranganath, Trujillo, & Knight, 2006; Wolk et al., 2009; Friedman, de Chastelaine, Nessler, & Malcolm, 2009; Church, Petersen, & Schlaggar, 2010; Friedman, 2013; Sastre, Wendelken, Lee, Bunge, & Ghetti, 2016; Wang, Johnson, de Chastelaine, Donley, & Rugg, 2016). Thus, the goal of the present study was to examine age- and performance-related differences in the neural activity associated with the accurate or inaccurate recall of contextual details.

In the following sections we review previous relevant literature using ERPs in 1) adults and 2) school-age children which provided motivation for the current study.

### **ERP Studies in Adults**

Work in adults has revealed differences in the amplitude and latency of neural activity associated with successful versus unsuccessful retrieval of contextual information. This effect has been found in multiple subcomponents of the ERP response. These effects are referred to as episodic memory (EM) effects. Specifically, EM effects most commonly reported are an early mid-frontal EM effect, a parietal EM effect, and a right frontal EM effect (for selected review see, Friedman & Johnson, 2000; Hayama, Johnson, & Rugg, 2008). An additional component,

the late negative posterior slow-wave (LPN) has also been reported in many recent ERP studies of episodic memory (for review, see Mecklinger, Rosburg, & Johansson, 2016).

Electrophysiological research examining the parietal EM effect indicates this effect is maximal over left hemisphere electrodes (Wilding, 2000; Murray, Howie, & Donaldson, 2015), with its amplitude modulated by the retrieval of source information of the recognized stimuli (e.g., male and female voices, Wilding & Rugg, 1996; location, Murray et al., 2015; studied paired associate, Rugg, Schloerscheidt, Doyle, Cox, & Patching, 1996). Further, the amplitude of the parietal EM effect is modulated by the amount of contextual information recalled (e.g., 1 detail versus 2 details; Wilding, 2000; Vilberg & Rugg, 2009). Thus, this component is thought to capture the extent to which a memory is contextually detailed or ‘episodic’ in nature (Donaldson, Wilding, & Allan, 2003; for review see Rugg & Curran, 2007).

The right frontal EM effect is a late occurring effect and is maximal in electrodes over the right hemisphere (Senkfor & Van Petten, 1998; Wegesin, Friedman, Varughese, & Stern, 2002). For example, Senkfor and Van Petten (1998) contrasted the right frontal EM effect in separate trial blocks assessing old/new recognition or source recognition (e.g., list membership) and showed that the right frontal effect was more pronounced for trials in which the source of the information was correctly recognized. This right frontal EM effect is hypothesized to serve as an index for retrieval success, as it is modulated by the quality (i.e., the precision; Murray et al., 2015) of the contextual information retrieved.

Finally, although the above-mentioned left parietal and right frontal EM effects show differences in responses to memories recalled with versus without details, this is not always the case for other EM effects. Research examining the early mid-frontal negative EM effect suggests that this component reflects retrieval of previously encountered stimuli based on familiarity,

rather than detailed recollection, as amplitudes are similar for items remembered regardless of whether the correct contextual details are recalled (Friedman, 2004). The early negative mid-frontal EM is also similar between original items and items that are highly similar to previously studied old items (i.e., “lures”) recalled as old (Curran, 2000; Nessler, Mecklinger, & Penney, 2001). For example, Curran (2000) presented words to subjects in either singular (e.g., “cat”) or plural forms (e.g., “birds”) then tested in the learned form (old; e.g., singular “cat”) or the opposite form (similar; e.g., singular “bird”). This EM effect differed between familiar and previously unseen words, but not between old words or similar words. Similarly, the LPN, a late negative posteriorly distributed effect, is thought to reflect additional processing required to reconstruct prior episodes (Mecklinger et al., 2016). This effect has been shown to be modulated by the search for task-relevant contextual information (Johansson & Mecklinger, 2003; Mecklinger, Johansson, Parra, & Hanslmayr, 2007), as opposed to the accuracy of the information retrieved (Cycowicz, Friedman, & Snodgrass, 2001; Friedman, Cycowicz, & Bersick, 2005). Specifically, LPN amplitude has been shown to be similar to source correct and source incorrect trials in adults (Friedman et al., 2005).

In sum, multiple EM effects have been reported in the ERP response in adults during memory tasks. However, the timing and location of these effects differ as do the nature of the response. Some EM effects appear to distinguish between items recalled with and without details (i.e., left parietal EM effect and right frontal EM effect), whereas other EM effects are similar between these conditions and instead distinguish between old versus new items regardless of details (i.e., early mid-frontal negative EM and LPN).

### **ERP Studies in School-aged Children**

Although ERP research in school-aged children (i.e., > 6 years) is more limited than in adults, this work has also documented multiple EM effects. Yet, these EM effects differ from those in adults. For example, Cycowicz, Friedman, and Duff (2003), tasked 9- to 10-year-old children, 12- to 13-year-old adolescents, and young adults with recalling whether an item had been presented in a given target color (exclusion task, e.g. red-other) and found that, compared to adults, a centro-parietal EM effect in children and adolescents showed longer latencies, and larger differences in amplitude between stimuli recalled with contextual details (i.e., the correct color) and new stimuli. Consistent with these findings, Czernochowski, Mecklinger, Johansson and Brinkmann (2005) found greater ERP latencies and amplitudes for a parietal EM effect in children ages 6 to 8 years and 10 to 12 years compared to adults (see also de Chastelaine, Friedman, & Cycowicz, 2007).

Research has also revealed age-related differences in the right frontal EM effect, such that this component only reliably differentiated between items recalled with contextual details and new items in adults, but not children or adolescents (Cycowicz et al., 2003; Sprondel, Kipp, & Mecklinger, 2011). Further, in a study by Haese and Czernochowski (2016) assessing EM effects in 7- and 10-year-old children and adults, the parietal EM effect was diminished in adults due to an overlap with LPN, while a parietal EM effect, but no comparable LPN, was observed in children. Finally, in a separate study, Sprondel, Kipp and Mecklinger (2012), examined EM effects in adolescents and adults and observed a reliable LPN only in adults that differed between old and new items, but did not differ between old items recalled with correct versus incorrect contextual details, suggesting maturation of the processes underlying the search and retrieval of contextual information through adolescence.

Together, these findings suggest that the neural resources recruited during the retrieval of contextual details can be measured using ERPs in children. However, they are not yet “adult-like” and continue to mature across development.

In addition to age-related differences, previous studies have highlighted the importance of considering task demands and the impact of performance on ERPs. For example, Mecklinger, Brunnemann, and Kipp (2011) found different ERP effects in 8- and 10-year-old children, and adults as a result of varying time constraints for a recognition task. When participants were instructed to give their response within a constrained time-window (i.e., a speeded condition) a mid-frontal old/new effect, but not parietal effect, was observed. However, when response time was unconstrained (i.e., non-speeded condition), a mid-frontal effect was observed in adults while a parietal EM effect was present in both children and adults. Relatedly, Czernochowski et al. (2005) found differences in the left parietal ERP effect as a result of differences in performance-level in 6- to 8- and 10- to 12-year-old children. In short, the left parietal effect was only observed when children’s performance was high; it was not observed when children with low performance were included. Thus, variations in findings across studies may result from differences in age as well as in task demands and performance (developmental versus performance effects).

Finally, the processes recruited to complete retrieval tasks (e.g., attention or familiarity/novelty-detection) may differ across ages and task demands and contribute to differences in EM effects. For example, work by Czernochowski, Mecklinger, and Johansson (2009) examining an early frontal subcomponent in 10- to 12-year-old children and young adults found more positive amplitudes for old compared to new stimuli in adults, with the effect was reversed in children. Czernochowski et al. (2009) proposed that this reversal was due to

differences in overall wave form morphology, plausibly due to ongoing maturation of the frontal lobes (e.g. Casey, Giedd, & Thomas, 2000; Casey, Tottenham, Liston, & Durston, 2005).

Interestingly, school-aged children's ERP morphology was similar to a negative ERP related to novelty and attention in infants (DeBoer, Scott, & Nelson, 2005) and younger children (e.g., 4-year-olds; Carver et al., 2003) discussed below. Consequently, this early frontal negative subcomponent may index attentional aspects of retrieval earlier in development in addition to the familiarity/novelty of stimuli that is indexed in adulthood.

### **Present Study**

Although behavioral research shows improvements in memory for details during early childhood (e.g., Riggins, 2014), the neural correlates that accompany these improvements are unclear. Specifically, it is not known whether there are differences in the neural activity supporting retrieval of contextual information in younger children (e.g., 4-5 years), before formal schooling (approximately 6 years). This is further complicated by the fact that, as children age, their performance improves. Therefore, it is unclear what aspects of differences observed in ERP responses can be attributed to age versus individual differences in performance. Thus, research investigating the development of detailed memories can reveal both how and why the ability to recall contextual details may differ across development.

The EM components discussed above in older children, adolescents, and adults, are not always identifiable in younger children, likely due to ongoing maturation of the brain and skull. However, there are similar components examined in studies of early-childhood that are thought to reflect the processing of memories. Namely, these studies in early-childhood examine EM effects in two developmental components: the negative component (Nc; e.g., Carver et al., 2003) and late slow wave (LSW; Marshall, Drumme, Fox, & Newcombe, 2002). The Nc is an early

negative component, which occurs approximately 350-800 ms after the onset of a stimulus and is typically maximal over frontal and central electrodes (see DeBoer, Scott & Nelson, 2007, for review). The Nc has been related to attentional processes that are modulated by memory (Bauer, Wiebe, Carver, Waters, & Nelson, 2003; Marshall et al., 2002; Riggins, Miller, Bauer, Georgieff, & Nelson, 2009). The LSW is a later component, which occurs approximately 900-1500 ms after the onset of a stimulus and is related to multiple aspects of source memory, such as memory updating (e.g., Nelson, Thomas, de Haan, & Wewerka, 1998; Carver, Bauer, & Nelson, 2000; for review see de Haan, 2007) and the retrieval of contextual details (e.g., Riggins, Rollins, & Graham, 2013; Riggins & Rollins, 2015).

Although it is unclear whether the parietal LSW and the parietal EM effects are related, both have been associated with memory for details in children and adults respectively. As reviewed above, in adults, the left parietal EM effect shows differences between items recalled with contextual details and the magnitude of this effect is related to behavioral performance. Similar findings have been observed in LSW in children. For example, in 5-year-old children LSW over lateral leads has been shown to differentiate between old items recalled with contextual details from both old items recalled without contextual details and new items, which did not differ from each other (Riggins, Rollins, & Graham, 2013). Moreover, LSW amplitude was positively related to children's source memory performance. Both of these effects are similar to findings in the left parietal EM effect in adults.

Subsequent studies have explored age-related differences in incidental retrieval of source memory (Riggins et al., 2009; Riggins & Rollins, 2015) and of intentional encoding of source memory (Geng, Canada, & Riggins, 2018) during this developmental period. These studies suggest EM effects in Nc and LSW differ as a function of age and condition. Briefly, these

studies found that Nc amplitude relates to participants' age (Geng et al., 2018) and differs between old and new items (Riggins & Rollins, 2015, Geng et al., 2018), but not between source correct and source incorrect trials (Geng et al., 2018). For LSW, amplitude relates to participants' age, with greater amplitudes observed in older versus younger children (Riggins et al., 2009), and differs between source correct and source incorrect conditions in older children during encoding (Geng et al., 2018) and incidental retrieval (Riggins & Rollins, 2015). In addition to age-related differences, previous work in 4- to 5-year-old children suggests differences in the neural correlates supporting incidental versus intentional retrieval of source memory in childhood (Robey & Riggins, 2016). Namely, an EM effect differentiating source correct and new items was observed in LSW over parietal leads during intentional source retrieval, but not during incidental retrieval. However, neither age- nor performance-related differences were examined.

As existing studies have not yet examined neural activity for items recalled with or without contextual details during intentional retrieval in early childhood, it remains unknown whether there are differences in the neural responses underlying source memory during this developmental period. Thus, the current study sought to examine EM effects supporting detailed memory in early childhood using an intentional source memory paradigm with a focus on both age- and performance-related differences in two prominent ERPs – the Nc and LSW. Given limited previous research on age- and performance related effects, no directional hypotheses were made a priori. Instead, the goal was to explore the extent to which neural activity supporting the retrieval of contextual details (as measured by differences in recall of items with and without contextual details) differed as a function of both age and individual differences in children's performance. This information will provide a critical foundation for future studies.

## Method

### Participants

Children were recruited from a major metropolitan area through a University maintained database of families interested in participating in research and the distribution of recruitment flyers. Participants were enrolled in a larger longitudinal study on memory and brain development. Prior to enrollment, children were screened to ensure they were not more than three weeks premature, had normal or corrected-to-normal vision, and had no diagnoses for any neurological conditions, developmental delays, or disabilities, which were the exclusion criteria for the study.

Participants included 94 4- to 8-year-old children ( $M = 6.03$  years,  $SD = 1.30$  years, 47 males, 47 females). Seven children were excluded because they did not provide usable behavioral data, with the inclusion criterion defined as  $p(\text{hits}) - p(\text{false alarms}) > 0$ . Twenty-six children were excluded due to having less than 10 ERP trials in the conditions of interest (see justification below), which resulted from a combination of movement artifact and low trial numbers. Thus, 61 children ( $M = 6.17$  years,  $SD = 1.28$  years, 31 males, 30 females) provided both complete behavioral and electrophysiological data and are included in this report. Although all subjects met the general item-memory behavioral criterion, some performed poorly on the source memory judgements. It was also the case that children in these age ranges had a difficult time staying still due to the length of the encoding and retrieval portions of the paradigm despite multiple reminders to stay still (see instructional script below). The majority of the sample was Caucasian (75%), from middle- to high-income households (median income greater than \$105,000 per year).

### Stimuli

Items were paired with character sources in order to assess memory for contextual details (i.e., the item recalled with the correct character). A total of 158 images of animals and objects determined to be age appropriate were selected from the Bank of Standardized Stimuli (BOSS; Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010). Of these 158 items, 58 were utilized for training and practice and divided into 20 practice items and two sets of 9 training items. The remaining 100 items were used for the task itself. To ensure observed effects were not the result of specific items tested in the task, 4 sets of 25 items were randomly created using the 100 task items. Three characters thought to be well known to children were used in the task: The Little Mermaid (i.e., Ariel), Mickey Mouse, and SpongeBob. To highlight the differences between the character sources, background color and item locations varied between characters. Specifically, items were presented to the left of two characters (Mickey Mouse and Ariel) and to the right of one character (SpongeBob), and items paired with Ariel were presented on a blue background, Mickey a red background, and SpongeBob a yellow background. However, neither background color nor location of the items was discussed with or emphasized to participants. At encoding, participants were presented with 75 stimuli paired to one of the three different character sources. Items were presented in three-blocks of 25 items. The character source remained constant throughout the duration of each block. The remaining item set of 25 items was presented as new during the retrieval portion of the task. At encoding, children were told correctly pairing the characters with their items later would help the characters get toy presents. Children were not told specific presents each character could receive. After retrieval, children saw the characters receive a present. Possible presents included a spinning toy, xylophone, stuffed giraffe, kite, beach ball, firetruck, pull-toy dog, toy robot, and tricycle.

To ensure observed effects were not the result of specific item-source pairings, two

versions of the task were included in the study. To create each version, the four sets of items were differentially assigned to the three characters or new condition. The order of the character-blocks within each version was the same for all participants but task version, and consequently sets of item-character pairings, was counterbalanced. Within each character-block, item presentation order was randomized using E-Prime (Psychology Software Tools, Pittsburgh, PA). Participants viewed all stimuli at eye level on a computer screen at a distance of 100 cm.

## **Procedure**

The University Institutional Review Board approved all procedures prior to data collection. Written informed consent was obtained from parents or guardians for all participants, and written informed assent was obtained from participants aged 7 years or older. Parents completed questionnaires regarding demographics and children's behavior during testing. After study completion, participants received monetary compensation, a toy prize, and a certificate with a picture of their brain waves. The focus of this report is results from an ERP retrieval paradigm, which consisted of an encoding task, followed by the collection of ERP and behavioral data for the intentional-retrieval portion of the task. The paradigm utilized is intentionally highly similar to one used by Geng and colleagues (2018), which focused on results of an ERP encoding paradigm in a different sample of young children. The one modification is that the retrieval paradigm presented in this report did not include a preceding item ("old"/"new") judgement, as in Geng et al. (2018); it required only a source judgement, similar to Mecklinger et al. (2007).

**Training.** Before beginning the task, participants completed a short training and practice session to ensure they understood task instructions. Both the encoding and retrieval portions of the task were introduced using a subset of the 58 training items. First the

Experimenter explained the task using the following instructions, “Today we’re going to play a fun game! The game has two parts. The first part is the learning part of the game and the second part is the matching part of the game. Today you’re going to play the learning part of the game before we put on the silly hat, and you will play the matching part while you’re wearing the silly hat.” During the encoding training phase, the Experimenter explained that participants would see items that belonged to different characters, saying, “First, in the learning part of the game, you will get to meet three characters and you will get to learn about the things that belong to them.” Then the experimenter told the children the three characters they would meet and asked if they were familiar with each character (e.g., “First you will meet Ariel the Mermaid. Do you know who Ariel is?”). Participants were told it was important to remember both the item and the character to which the item belonged, “Make sure you pay attention to which things belong to which character! This is important because Ariel, SpongeBob, and Mickey need your help remembering which things are theirs! If you can help them remember which things are their own things, they will each get a special present.” The Experimenter then asked if the participant had any questions. Once more before beginning training, the Experimenter reminded the child the importance of remembering both the character and their items, “So make sure to pay attention to the things, but also pay extra special attention to who they belong to so you can help Ariel, Mickey, and SpongeBob get a present.”

The on-computer training then began. First, the Experimenter showed the participant a character alone on the screen and identified the character by name and prompted that the items were important to the character (e.g., “This is Mickey, and here are some of his favorite things!”). Then, two items were sequentially presented next to the character and the Experimenter verbally labeled each item (see Figure 1A). The Experimenter repeated this

process for the remaining two characters, which resulted in a total of 6 character-item pairs.

Immediately following encoding training, the Experimenter explained the retrieval phase to participants, “Now you’re going to play the matching part of the game! You’re going to see some more pictures of things. Some of them you saw earlier, and they belong to SpongeBob, Mickey, or Ariel, and some of them are new and belong to someone else. After you see the thing, you will see the characters again, and I’m going to ask you who each thing belongs to SpongeBob, Mickey, Ariel, or someone else. Make sure you only give me your answer after you see the characters come onto the screen and try your very best so that you can help the characters get presents after the game.” Participants then completed the retrieval training phase. For retrieval training, participants were presented with 6 old items (i.e., items shown with a character during encoding training) and 3 new items. For each item, they were asked to identify if the item had been presented with one of the three characters or someone else. Participants were told if the item belonged to SpongeBob, Mickey Mouse, or Ariel, they should select the correct character (source memory). If the item was not paired with one of the three characters, they should select “someone else,” who was represented by a gender-ambiguous cartoon silhouette (item memory, see Figure 1B). The Experimenter corrected inaccurate responses during retrieval training. If the child selected a character source for a new item the experimenter would say, for example, “Are you sure? I don’t remember seeing that item with Mickey/Ariel/SpongeBob. This item is new and belongs to ‘someone else’.” If the child selected the wrong character source or someone else for an old item the Experimenter would say, for example, “Are you sure? I remember seeing that item with SpongeBob. The kite belongs to SpongeBob.”

**Practice.** Following encoding and retrieval training, participants practiced both portions of the task. The Experimenter asked if the child understood the game, then proceeded to explain

the practice portion of the task, “Now we’re going to practice the game one more time, but this time, the game will have more things, because the real game will have lots of things! Also, now you should practice being very still during the matching part of the game, because you will have to be very still when you are wearing the silly hat! First is the learning part! We’re going to see Ariel, SpongeBob, and Mickey again. Don’t forget to pay attention to whose things are whose so you can help the characters win a present!” During encoding practice, 5 different items were presented with each of the three characters. Participants were instructed to observe and remember item and character pairings.

After encoding practice, the experimenter reminded participants of the rules of the retrieval portion of the task, “Now we’re going to play the matching part of the game again! This time, I can’t tell you if you are right or wrong. If you are not sure, it’s okay to make your best guess. Don’t let the game trick you!” During retrieval practice, participants were required to make source memory judgments on 20 practice items (5 old items per character, 5 new items). Inaccurate responses were not corrected during retrieval practice. If participants did not reach a minimum of 80% accuracy the Experimenter re-explained the task and participants completed an additional practice session with different practice stimuli before proceeding to the test. Of the analyzed sample, 24 of 61 children completed two rounds of practice.

**Encoding.** After completing training and practice, participants were told that the task would begin, “Now we’re going to play the game for real! You’re going to play the learning part of the game first, then we’ll put on the silly hat, and then we’ll play the matching part of the game! Let’s start the learning part of the game. Don’t forget to pay attention to which things belong to which characters so they can win presents!” Participants were again instructed to observe and remember each item-character pairing. The use of strategies was not discussed with

participants; thus, no particular strategy was suggested in order to accomplish the task.

Participants were then asked to remain as still as possible and informed that they would get a short break, lasting approximately 1 minute, between each character-block. Within each block, only one character was presented and paired with 25 items that “belonged to them.” This resulted in 75 total encoding trials across all three character-blocks (see Figure 1 for schematic). Each trial consisted of the presentation of an item with a character (1500 ms) followed by the presentation of a fixation cross that remained on the screen during the inter-stimulus interval (1000-2000 ms, with an average of 1500 ms).

**Retrieval.** Electroencephalography (EEG) was recorded during the retrieval phase of the task. Retrieval began approximately 15 minutes after participants completed the encoding phase. Participants were reminded that the matching part of the game would take place after capping, “Now we’re going to put on the silly hat and then play the matching part of the game.” Participants were fitted with a stretchy Lycra cap appropriate for their head circumference containing 64 recording sensors. Electrodes were placed in the cap. Participants were asked to remain as still as possible. In addition to providing time to place the electrodes, the delay ensured working memory did not drive task performance.

Before starting the retrieval portion of the task, participants were reminded of the task rules by the Experimenter, “Now you’re going to play the matching part of the game! Remember, you’re going to see some more pictures of things. Some of them you saw earlier, and they belong to SpongeBob, Mickey, or Ariel, and some of them are new and belong to someone else. After you see the thing, I’m going to ask you who each thing belongs to, SpongeBob, Mickey, Ariel, or someone else. Make sure you only give me your answer after you see the characters come onto the screen and try your very best so that you can help the characters get

presents after the game. Also be very still!”

Items were presented on the screen for 1500 ms. After a delay of 400-600 ms (with an average delay of 500 ms to control for expectation effects), the three source characters and “someone else” were presented on the screen. Participants were asked to verbally indicate to whom the item belonged, which could be one of the three character sources or someone else. Participants were instructed to wait until the item had been presented and the screen displayed the three character sources and “someone else” to provide a response. The four choices remained on screen until participants gave a response, which was recorded by the Experimenter using a keyboard. During the inter-stimulus interval, a fixation cross was displayed on the screen.

(Figure 1 about here)

We were interested in examining item memory (old/new) and source memory (source correct/source incorrect) performance. As such, variables of interest included: old items participants accurately recalled as having belonged to a character (‘hits’), new items participants accurately recalled as belonging to “someone else” (‘correct rejections’), new items incorrectly paired with a character (‘false alarms’), and old items incorrectly attributed to “someone else” (‘misses’). Stimuli accurately identified as old (‘hits’) were further categorized as ‘source correct’ if the participant correctly identified the character with whom the item was presented at encoding, or ‘source incorrect’ if the participant correctly identified the item as belonging to one of the three characters but misattributed the item to the incorrect character. Item memory (i.e., if an item was remembered regardless of correct source) was indexed using a measure of discrimination,  $Pr = H - FA$ , where  $H$  represents the hit rate and  $FA$  the false alarm rate (Snodgrass & Corwin, 1988). Item memory was collected to account for variability in source performance resulting from the number of items correctly identified as old. To index source

memory (i.e., if an item was remembered with the correct character), the percentage of source correct trials was calculated by dividing the number of source correct trials by the number of total hit trials (i.e., old items recalled with either correct or incorrect source details; Mecklinger et al., 2007; Geng et al., 2018). To account for differences in overall item memory, item memory was controlled for in all analyses. Bias, or the probability of a subject identifying an item as belonging to character when uncertain was defined using the measure  $Br = FA / [1 - (H - FA)]$  where values higher than .50 indicate a more liberal bias (Snodgrass & Corwin, 1988).

### **EEG Data Recording and Analysis**

EEG recording and analysis methods were intentionally similar to those reported by Geng and colleagues (2018). EEG was continuously recorded from 64 Ag/AgCl electrodes as well as two vertical and two horizontal electrooculogram channels at a sampling rate of 512 Hz during retrieval rather than encoding. Brain Electrical Source Analysis (BESA) software (MEGIS Software GmbH, Gräfelfing, Germany) and EEGLab (Delorme & Makeig, 2004), a MATLAB toolbox, were used for preprocessing and data reduction. Bad channels were interpolated, and ocular artifacts were corrected using BESA. A maximum of 10 bad channels (<15.6% channels) were allowed for inclusion in the dataset. Additional preprocessing was completed using EEGLab. Continuous EEG data were low-pass filtered at 0.1 Hz and high-pass filtered at 30 Hz. Filtered data were segmented into epochs starting 100 ms before stimuli onset and ending 1500 ms after stimuli onset. Segments were rejected if any artifact was detected (e.g., blink) or if the amplitude exceeded 200 microvolts ( $\mu V$ ) or was below  $-200 \mu V$ . For each channel, averaged data of all segments were re-referenced to the average potential of all channels.

**Waveform Analysis.** ERPs were formed by averaging source correct and source incorrect trials. To draw connections to previous literature investigating episodic memory effects

using the 10-20-system montage of electrodes for collecting EEG data, data from nine electrodes were selected for further statistical analysis: bilateral frontal (F3 and F4), central (C3 and C4), and parietal (P3 and P4) electrodes, and three midline (Fz, Cz, and Pz) electrodes (e.g., Czernochowski et al., 2005; Rollins & Riggins, 2013). Two developmental ERP components, Nc and LSW, were the focus of this study. Average amplitude of Nc was calculated for both source conditions 350-800 ms after the onset of stimuli. Nc amplitude is negative in frontal-central leads and positive in parietal leads due to polarity inversion. Average amplitude of LSW was calculated for both source conditions between 900-1500 ms. LSW amplitude is positive in frontal-central leads but negative in parietal leads due to polarity inversion. Time windows for Nc and LSW were selected based on previous literature on memory and ERPs in young children (Marshall et al., 2002; Geng et al., 2018).

Participants with fewer than 10 trials in any condition were excluded from ERP data analysis (for a detailed explanation of this recommendation see DeBoer et al., 2005; DeBoer et al., 2007). Participants contributed an average of 19.95 source correct trials ( $SD = 7.39$ , range= 10-39) and 18.69 source incorrect trials ( $SD = 5.83$ , range= 10-43). Average amplitude in  $\mu V$  served as the dependent measure, as it is more robust to differences in trial numbers between conditions compared to other measures (e.g., peak amplitude; see Luck, 2014).

### **Statistical Analysis**

All statistical analyses were conducted in IBM SPSS Statistics 20 (IBM Corp., Chicago, IL). Linear regression models were used to analyze the age-related differences in item memory performance (i.e., Pr), source memory performance (i.e., percent of source correct trials), and response bias (i.e., Br). Mixed-model repeated-measures general linear models (GLM) were used to examine mean amplitudes associated with the Nc and LSW components for correct and

incorrect source memory. This allowed for both categorical and continuous predictors to be entered as within- or between-subject predictors. To test amplitude differences, mixed-model repeated-measures GLMs were conducted on average amplitude in each time window in a 2 Condition (source correct, source incorrect)  $\times$  3 Coronal Plane (frontal, central, parietal)  $\times$  3 Sagittal Plane (left, middle, right)  $\times$  Age  $\times$  Performance (source correct percent) design. Condition, Coronal Plane, and Sagittal Plane were within-subject predictors, and Age and Performance were included as continuous between-subject predictors to preserve variability of the data. To account for variation in source performance due to item memory, the number of total hit trials was included as a covariate. To account for differences in the number of ERP trials contributing to the analyses between participants, the number of source correct ERP trials and source incorrect ERP trials were also included as covariates. In probing significant interactions, data were split by Coronal Plane or Sagittal Plane when possible to maintain the continuous nature of the Age and Performance variables. When necessary, a median split was used to probe interaction effects for possible differences between younger and older children (median = 5.86 years), and high- and low-performing groups on the dependent variable of interest (i.e., source correct percent; median = 0.53). While Age and Performance were entered as continuous variables in the initial analyses, Age and/or Performance groups were entered into follow-up models for significant interactions as between-subject categorical predictors. As an a priori design decision, we examined only main effects or interactions of Condition, Age, and Performance. When the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied (Greenhouse & Geisser, 1959).

## **Results**

### **Behavioral Performance**

There was a significant positive relation between Pr and age ( $r(61) = .38, b = .06, t = 3.13, p < 0.01$ ), suggesting that as age increased, the ability to discriminate old and new items increased. The relation between source memory performance and age was not significant ( $r(61) = .16, b = .01, t = 1.23, p = 0.22$ ). Additionally, response bias Br did not relate to age ( $r(61) = -.09, b = -.02, t = -0.71, p = 0.48$ ), with participants showing a conservative bias. See Table 1 for descriptive statistics for all participants (used in initial analyses) and by age- and performance-groups (used for follow-up analyses).

(Table 1 about here)

### **ERP Source Memory: Source Correct vs. Source Incorrect waveform analysis**

*Nc component (350-800 ms).* The GLM did not reveal significant main effects or interactions of Condition, Age, and Performance.

*LSW component (900-1500 ms).* The GLM revealed a Condition  $\times$  Sagittal Plane  $\times$  Performance interaction ( $F(2, 108) = 5.34, p = 0.01, \eta^2 = 0.09$ ) and a Condition  $\times$  Coronal Plane  $\times$  Age  $\times$  Performance interaction ( $F(2, 108) = 3.56, p = 0.04, \eta^2 = 0.06$ ). Follow-up analyses for the first interaction were conducted by Sagittal Plane. These revealed a Condition  $\times$  Performance interaction in the left sagittal plane ( $F(1, 54) = 6.13, p = 0.02, \eta^2 = .10$ ) and right sagittal plane ( $F(1, 54) = 4.08, p = 0.048, \eta^2 = 0.07$ ), and no effect in the middle plane ( $p > 0.63$ ). By using low- and high- performing groups (derived via median split, described above in Method) to examine the interactions in left and right leads, it appeared that effects were the result of a greater difference between source correct and source incorrect conditions in low-performing compared to high-performing children. Specifically, in left leads LSW amplitude was more negative for the source incorrect versus source correct condition in low-performing children, whereas in right leads amplitude was more negative for the source correct versus source incorrect

condition (Figure 2). Average amplitude between conditions did not appear to differ for high-performing children.

(Figure 2 about here)

Follow-up analyses for the second interaction were first conducted by Coronal Plane. These analyses indicated a significant Condition  $\times$  Age  $\times$  Performance interaction in the parietal plane ( $F(1, 54) = 6.74, p = 0.01, \eta^2 = 0.11$ ), a marginal interaction in the frontal plane ( $p = 0.07$ ), and no significant interaction the central plane ( $p > .97$ ). To further examine these effects, similar to analyses performed above, participants were divided into younger and older age groups and low- and high-performing age groups defined using a median split on appropriate variables. Results revealed a greater difference in mean LSW amplitude between source conditions for younger children compared to older children and was specific to younger, low-performing participants. Specifically, at parietal leads, mean amplitude was more negative for the source correct versus source incorrect condition (Figure 3).

(Figure 3 about here)

## **Discussion**

The present report contributes to our understanding of the neural correlates underlying young children's ability to recall contextually detailed memories. The findings suggest that *both* age- and performance- related differences exist in the neural signature recorded during retrieval processes. Specifically, EM effects in the LSW, but not Nc, were influenced by age and performance. LSW has previously been related to source memory, has been shown to reflect the updating of memories, and has been shown to be sensitive to age during this period of childhood (Marshall et al., 2002; DeBoer et al., 2005, 2007; Riggins et al., 2013).

First, effects of performance were observed in that low-, but not high-, performing children showed differences in LSW to items recalled with versus without contextual details in both left and right hemispheres. However, the direction of these effects differed between hemispheres. In the left hemisphere, LSW amplitude was more negative for the source incorrect versus source correct condition, whereas in the right hemisphere amplitude was more negative for the source correct versus source incorrect condition. Previous research in infants (Carver, Meltzoff, & Dawson, 2006), school-aged children (Czernochowski et al., 2009), and adults (Curran, 2004) has reported similar patterns for ERPs related to memory (i.e., opposite amplitude effects in left versus right hemispheres). It is possible that these apparent hemispheric differences reflect differences in the neural areas recruited during this task in low-performing children (see below for discussion), in the confidence children had in their source judgement (Curran, 2004), or in the specificity of the information retrieved (Ranganath, 2004). However, these differences may have also arisen due to variations in comprehension of the task, how children perceived the task, or how the task was accomplished. Future research is needed to examine these and other possible explanations.

Second, effects of age, revealed that younger, but not older, children showed differences in LSW for source correct versus source incorrect conditions, particularly at parietal leads. However, this effect was qualified by performance, as it held only for younger children who performed poorly on the task. Specifically, mean LSW amplitude for the source correct condition was greater than that for source incorrect condition in younger, low-performing children. A similar effect has been observed in older low-performing adults (Wolk et al., 2009), and was suggested to represent recruitment of additional neural resources. There are several possible explanations for why this effect was only observed in young, low-performing children. For

example, it may reflect inefficient processing, or it may reflect compensatory activity due to the combination of attempted retrieval plus increased demands placed on neural resources engaged to complete this task or a combination of both. For example, work by Riggins et al. (2009) in 3- and 4-year-old children found that increased task demands (i.e., decreased number of facilitatory relations in a to-be-remembered temporal sequence), modulated LSW activity. Greater differences were observed in the difficult (i.e., less facilitating) condition than in the easier (i.e., more facilitating) condition when compared to LSW activity for arbitrary events (i.e., no facilitation). In the current study, younger low-performing children showed the greatest difference between trials in which they correctly versus incorrectly recalled contextual details. A potential explanation for this finding is that differences in LSW activity between conditions reflect additional processing demands encountered when these children attempted to update their memory for the character corresponding to a given item and/or their difficulty in retrieving their memory for the correct source. In other words, it is possible that while LSW activity in young, yet high-performing, children and older children may reflect the attempt to recollect the contextual details surrounding items, LSW activity in young, poor performing children reflects inefficient processing and/or compensatory engagement of different or additional processes that varied between the conditions. Unfortunately, these interpretations are speculative as we could not directly test them because we did not systematically manipulate task demands and there was not a sufficient number of trials to examine LSW activity in relation to new items (Czernochowski et al., 2005). These comparisons would be important to include in future investigations as they would allow for stronger conclusions to be made about the observed effect.

The Nc did not reveal significant differences between source correct versus source incorrect conditions, nor effects of age or performance. While this component was observed, the

lack of differences in  $N_c$  suggests that this component (which may reflect attention or familiarity) does not reliably differ across age or performance during intentional source memory retrieval in early childhood. It is possible that differences in  $N_c$  may be more apparent when this effect is examined in younger (i.e., < 4 years) or older (i.e., > 9 years) children or when these conditions are contrasted with new items. Future work is needed to address these and other possibilities.

Consistent with previous work, children's ability to recall items, irrespective of contextual details (i.e., source), improved with age (e.g., Riggins, 2014). However, there was not a significant improvement in children's ability to recall both an item and the contextual details surrounding that item (i.e., to which character an item belonged). Although behavioral studies focused on the improvement of children's source memory have documented improvements in this ability during early childhood (i.e., 4-8 years; Riggins, 2014), this effect was not observed in the present investigation (Geng et al., 2018; Geng, Redcay, & Riggins, 2019 for similar findings). It is possible that the nature of the current task diminished the ability to detect such an effect. Specifically, the present study required the children to view many trials (75) during relatively quick presentations (1500 ms). In contrast, behavioral studies require fewer trials (e.g., 12; Riggins, 2014), longer delays (Riggins et al., 2018), and/or longer possible encoding and/or retrieval durations (several seconds each; Riggins, 2014). Finally, participants in the present study showed an overall conservative response bias during this task, which did not differ by age. It is possible that children made source judgements for this task only when they felt certain in their memory for the contextual details, limiting the ability to observe improvements in source memory ability. Thus, differences in the number of to-be-remembered items, timing constraints,

and/or response bias may have impacted performance and decreased the ability to observe age-related differences.

It is also possible that a participant may fail to accurately identify the detail tested in the paradigm (e.g., a character), but may recall a different contextual detail that was not explicitly probed by the task (i.e., noncriterial recollection; e.g., Yonelinas & Jacoby, 1996; Gruppuso, Lindsay, & Kelley, 1997). That is, a child may recall a contextual detail related to the event not tested at retrieval (e.g., the temporal order of the items learned), thus not capturing the complete picture of improvements in memory for details.

There were several limitations of the present study. First, the task used in the present study was designed to maximize our ability to examine differences in the neural activity supporting children's ability to remember source details (75 possible source decisions) and minimizing the number of new items (25). Due to this a priori design decision, the sample of children with useable ERP data corresponding to correctly rejected items (25 possible correct rejection decisions) was too small to compare this neural activity against source correct and source incorrect conditions. Studies examining the development of neural correlates of detailed memory in early childhood might consider utilizing a task that better allows for these comparisons.

Second, the average number of trials contributing to the analyses in this study ( $n_{\text{source correct}} = 19.95$ ,  $n_{\text{source incorrect}} = 18.69$ ) are lower than those studies examining EM effects in older children ( $n_{\text{source correct}} = 33$ ,  $n_{\text{source incorrect}} = 38$ ), adolescents ( $n_{\text{source correct}} = 42$ ,  $n_{\text{source incorrect}} = 41$ ), and adults ( $n_{\text{source correct}} = 45$ ,  $n_{\text{source incorrect}} = 45$ ; e.g. de Chastelaine et al., 2007). Although these trial numbers are similar to previous studies with young children (e.g., Marshall et al., 2002) and we attempted to account for the influence of trial number contributed by each participant and the

use of mean amplitude, the overall results may be less robust than those reported later in development. The lower number of trials is partially due to the difficulty for young children staying still for the duration of the task.

Third, although the present study offers insight into the neural activity supporting the ability to recall contextually rich details in early childhood, it does not assess the change that occurs within this limited age range. Future studies examining the neural correlates supporting the ability to recall the details surrounding memories should work to bridge the gap between research early in development to later developmental periods to better understand how the morphology, timing, and nature of EM effects change in relation to source memory.

Despite these limitations, findings from the current study highlight the importance of considering both age and performance in future studies examining memory development in early childhood. Many previous studies report differences in EM effects between children and adults or younger children and older children without taking performance into account. In all of these studies, younger participants performed worse than older participants. Therefore, it cannot be concluded that differences in age explained the previous effects. It remains possible that performance (which often correlates with age) was the source of the difference. Results from the present study highlight the importance of considering age and performance in ERP studies of memory and contribute toward the goal of connecting ERP research across childhood, through adolescence and into adulthood.

### **Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1

*Descriptive statistics for all participants (used for initial analyses), and age- and performance-groups (used for follow-up analyses)*

Group	Measure			
	<i>n</i>	Pr	Source Accuracy (proportion)	Br
All Participants	61	.53 (.21)	.52 (.11)	.23 (.20)
Younger Low-Performing	19	.40 (.22)	.44 (.11)	.26 (.21)
Younger High-Performing	11	.50 (.14)	.62 (.07)	.18 (.21)
Older Low-Performing	11	.54 (.20)	.43 (.09)	.26 (.25)
Older High-Performing	20	.67 (.14)	.59 (.07)	.19 (.18)

*Note.* Standard deviations (SD) are in parentheses. Pr: Discrimination index; Br: Response bias index. Median age = 5.86 years. Median source memory performance = 0.53. Age and performance groups were only used for probing significant interactions and illustrative purposes (i.e., age and performance were continuous in initial analyses and in follow-up analyses whenever possible).

## Figure legends

Figure 1. Schematic representation of the A) encoding and B) intentional retrieval portions of the task.

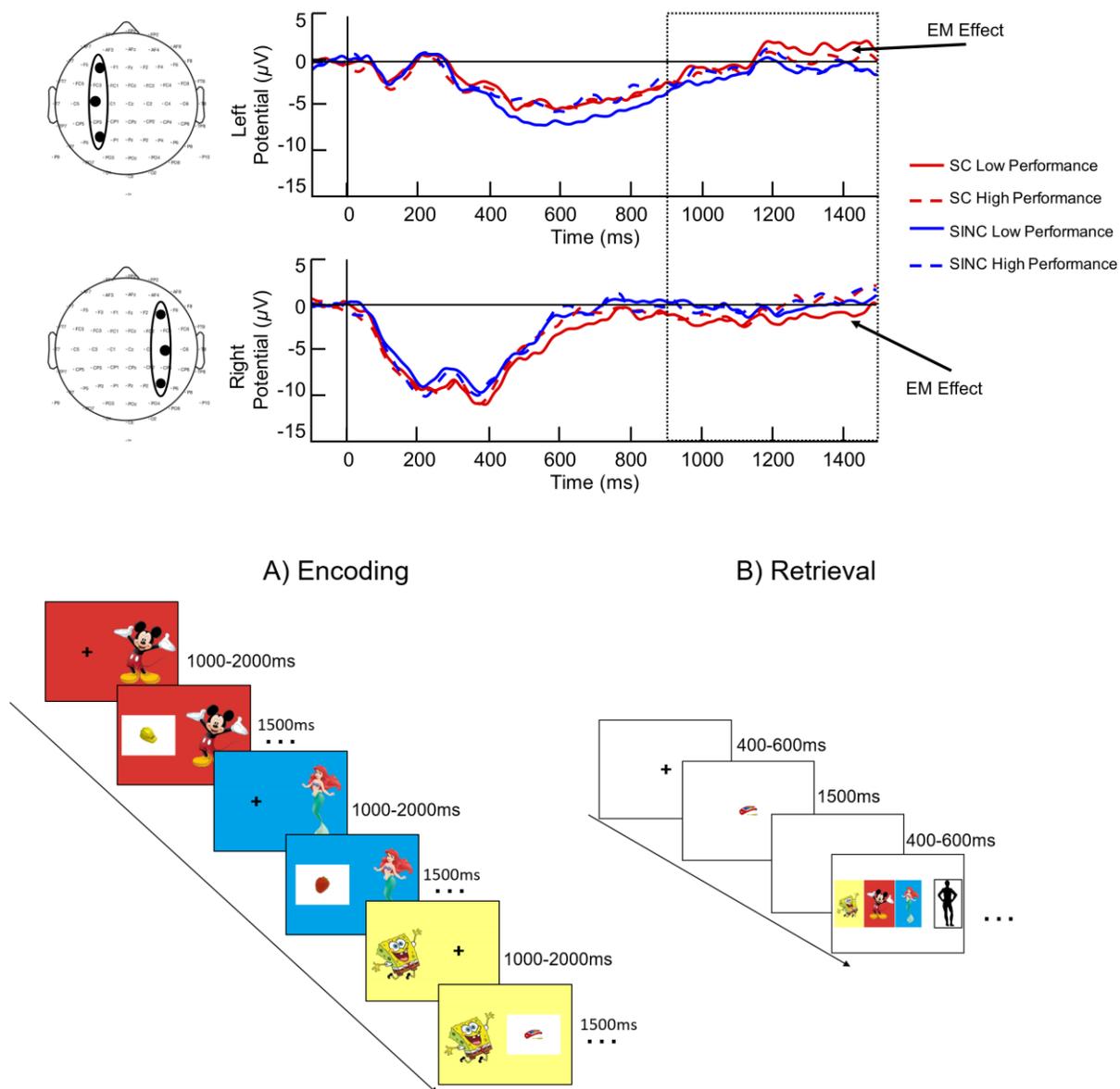


Figure 2. ERP waveforms for high- and low-performing participants (defined by a median split  $median_{source} = 0.53$  for illustrative purposes) averaged across right (F4, C4, P4) and left (F3, C3,

P3) electrodes, respectively. Responses for low-performing children corresponding to the identification of old items remembered with the correct source (source correct) are depicted in solid red. Responses for high-performing children corresponding to the identification of old items remembered with the correct source (source correct) are depicted in dashed red. Responses for low-performing children corresponding to the identification of old items remembered with the incorrect source (source incorrect) are depicted in solid blue. Responses for low-performing children corresponding to the identification of old items remembered with the incorrect source (source incorrect) are depicted in dashed blue. For LSW, ERPs were evaluated between 900 and 1500 ms.

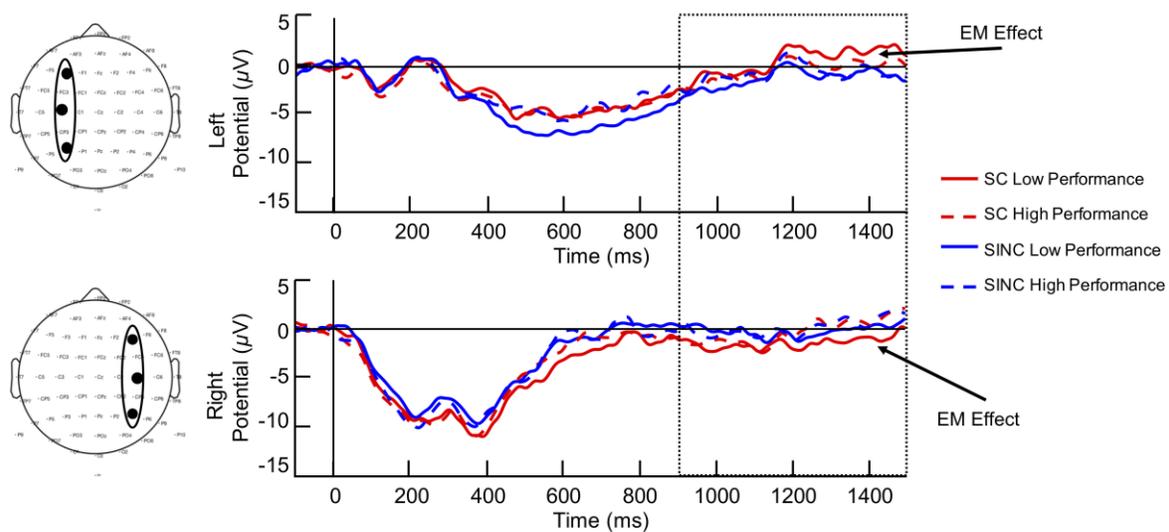
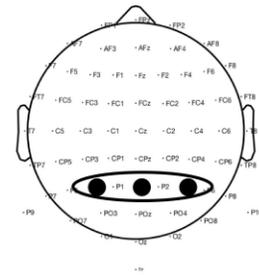
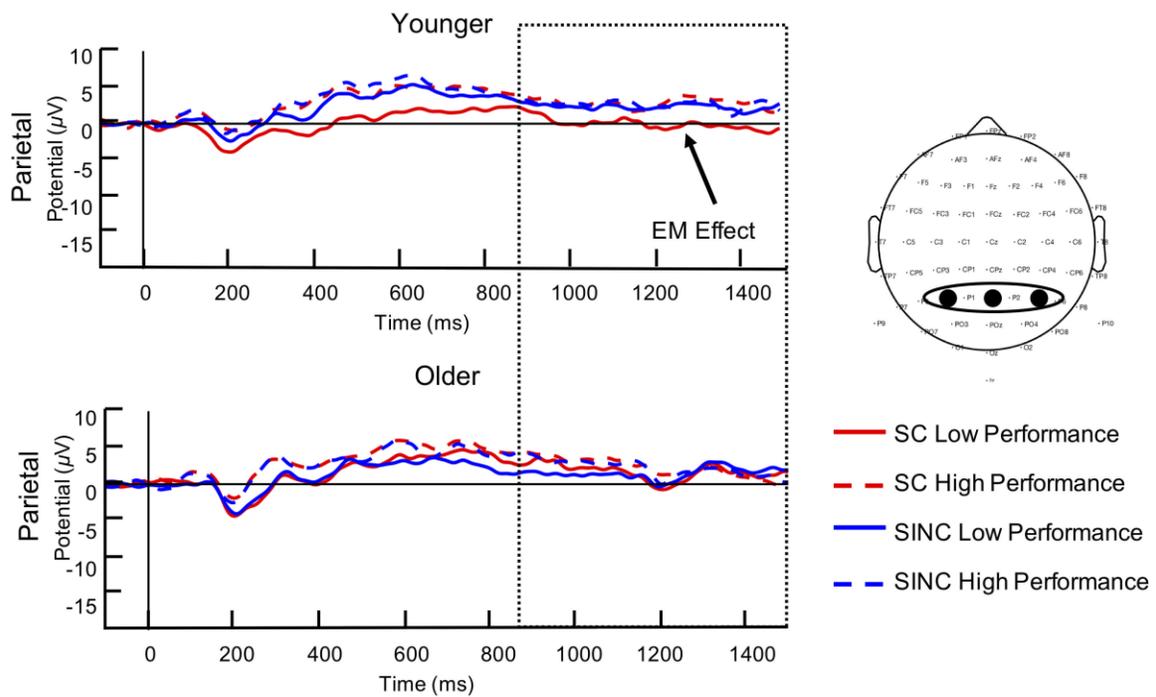


Figure 3. ERP waveforms for A) younger and B) older high- and low-performing participants (defined by a median split  $median_{source} = 0.53$ ,  $median_{age} = 5.86$  years for illustrative purposes). ERPs are averaged across parietal (P3, Pz, P4) electrodes. Responses for low-performing children corresponding to the identification of old items remembered with the correct source (source correct) are depicted in solid red. Responses for high-performing children corresponding

to the identification of old items remembered with the correct source (source correct) are depicted in dashed red. Responses for low-performing children corresponding to the identification of old items remembered with the incorrect source (source incorrect) are depicted in solid blue. Responses for low-performing children corresponding to the identification of old items remembered with the incorrect source (source incorrect) are depicted in dashed blue. For LSW, ERPs were evaluated between 900 and 1500 ms.



- SC Low Performance
- - SC High Performance
- SINC Low Performance
- - SINC High Performance