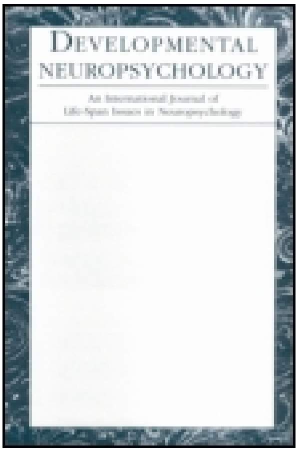

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Electrophysiological Investigation of Source Memory in Early Childhood

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Electrophysiological Investigation of Source Memory in Early Childhood

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Recollection is well-characterized in adults and school-aged children, yet little is known about how this ability develops in early childhood. This study utilized a behavioral source memory paradigm and event-related potentials (ERPs) to examine recollection in early childhood. ERPs were compared between items whose context was remembered and forgotten as well as new items. Activity late in the electrophysiological response showed a "recollection" effect, which differentiated items with correct source judgments from all others. This study is unique in that it is the first to provide information regarding the spatiotemporal dynamics of the neural networks underlying recollection during early childhood.

Memory is a cornerstone ability on which we build knowledge of ourselves and the world around us. The importance of memory is especially apparent when the ability is impaired or lost. Episodes of forgetting can range from being mildly disruptive (e.g., forgetting where you placed your car keys) to embarrassing (e.g., forgetting the name of a spouse of an important colleague) to debilitating (e.g., forgetting significant events from your life, as observed in severe amnesic disorders). Such failures in memory have been shown to significantly impact life success and mental health (Gathercole, 1998; Naismith et al., 2003; McKenna et al., 1990). Given its importance, memory has been studied extensively.

One finding that is particularly striking given the importance of memory is its protracted developmental course (see Bauer, 2006 for review). Memory, particularly recollection (or the ability to recall the contextual details associated with an event), does not reach maturity (i.e., adult levels) until after adolescence (Ghetti & Angelini, 2008; Ghetti, DeMaster, Yonelinas, & Bunge, 2010). This extended trajectory has been associated with the prolonged development of brain networks critical for memory performance including both subcortical (e.g., hippocampus) and cortical (e.g., dorsolateral prefrontal cortex) regions (Ghetti et al., 2010; Menon, Boyett-Anderson, & Reiss, 2005; Ofen et al., 2007). Evidence supporting this developmental profile and these brain–behavior relations comes from a variety of different sources. In adults and school-aged children, converging work stems from behavioral (Ghetti & Angelini, 2008), electrophysiological (event-related potential [ERP], Cycowicz, Friedman, & Duff, 2003; Czernochowski, Mecklinger, Johansson, &

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Brinkmann, 2005; Mecklinger, Brunnemann, & Kipp, 2011; Sprondel, Kipp, & Mecklinger, 2011), and neuroimaging (functional magnetic resonance imaging [fMRI], Ghetti et al., 2010; Menon et al., 2005; Ofen et al., 2007) paradigms. Research in infancy and early childhood has relied more exclusively on behavioral (Bauer, 2006) and electrophysiological (de Haan, 2007; DeBoer, Scott, & Nelson, 2005; 2007) paradigms (although some neuropsychological work with populations at-risk for memory or hippocampal impairment has been done (e.g., Adlam, Vargha-Khadem, Mishkin, & de Haan, 2005; Rose, Feldman, Jankowski, & Van Rossem, 2011; Riggins, Miller, Bauer, Georgeiff, & Nelson, 2009a). Although behavioral and electrophysiological approaches are used across the life span, the theoretical perspectives, paradigms, and particular methods used are quite different between older and younger subjects. These differences make linking findings from studies that include older and younger subjects difficult, if not impossible. This situation is problematic as it impedes a full understanding of memory, its neural bases, and development.

Current literature on recollection exemplifies this theoretical and methodological disconnect across development. The term recollection refers to the cognitive process that allows individuals to retrieve information about distinct features associated with an event (Yonelinas, 2002). It is through recollection that individuals are able to recover "qualitative" information, such as the temporal or spatial context surrounding an event or the novel associations between different components of an event. This ability gives rise to the rich phenomenological experience associated with recalling past events. Despite the fact that recollection is well characterized both theoretically and empirically in adults (see Yonelinas, 2002), no systematic studies of age-related changes in recollection during infancy and early childhood currently exist. This likely stems from the fact that most empirical paradigms designed to examine recollection directly have not been used with children this young due to their high cognitive demands. Based on this methodological challenge the theoretical distinction between recollection and familiarity (dual process models of memory) has largely been ignored in developmental literature (Brainerd, Reyna, & Howe, 2009; Newcombe & Crawley, 2007). In general, most research that has been conducted on the development of memory in younger preschool children has focused on the distinction between procedural and declarative memory (Bauer, 2006).

Because electrophysiological measures can be obtained from infancy through adulthood, this method may be ideal for examining the development of recollection across the lifespan. However, large differences exist in theories and methods used in studies with younger and older subjects. These differences need to be considered when comparing results across age groups. To assist in this endeavor, in the following sections, we review ERP studies from four different age groups: adults, school-aged children (6 years and up), preschool children (2–5 years), infants (0–2 years). For each age group we point out some of the major findings, including developmental changes when known, and highlight methodological differences that arise due to limited attentional capacities and motor abilities in infants and young children.

ADULTS

Electrophysiological studies in adults using the ERP technique typically require participants to encode a large number of stimuli (visual or auditory) and, after a short delay (on the order of minutes), make judgments about items. These judgments can be subjective in nature (e.g., asking participants if they "remember" the item was on the list or simply "know" it was there, remember/know paradigm) or objective in nature (e.g., asking participants if they have previously encountered a specific stimulus before, referred to as an old/new judgment, followed by questions regarding the contextual details associated with the item, such as where in the list it occurred, referred to as a source judgment). ERPs are commonly recorded during both encoding and retrieval and behavioral responses are acquired concurrently. ERPs are then analyzed, comparing "remember" to "know" responses or source-correct to source-incorrect responses to determine the relative contribution of recollection.

These studies have documented differential responses in the ERP waveform (termed episodic memory or "EM" effects) for judgments reflecting recollective memory processes ("remember" or source-correct responses) versus other memory processes, such as familiarity (i.e., "know" or "source-incorrect" responses, see Friedman & Johnson, 2000 for review). The first EM effect to appear in the waveform does not show differences between previously encountered stimuli ("remember/know" or source-correct/source-incorrect), but does differentiate them from new items (and is therefore termed an "old/new effect"). It is present 420–590 msec after stimulus onset and is maximal over left prefrontal-central scalp locations. The second EM effect differentiates between items given "remember" or source-correct judgments and those that were given "know" or source-incorrect judgments and new items (termed a "recollection effect"). It begins 420–490 msec after stimulus onset and extends for several hundred milliseconds over left parietal regions. Its amplitude is related to retrieval success. The third EM effect also differentiates "remember" or source-correct judgments and those that were given "know" or source-incorrect judgments and new items and is thought to reflect post-retrieval monitoring (although consensus regarding this functional significance is still lacking, Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999; Wilding & Rugg 1996a, 1996b). It begins around 500–590 msec after stimulus offset, lasts until the end of the recording epoch, and is maximal over right frontal-central regions. These findings provide support for dual-process models of memory, which suggest that recollection and familiarity contribute to successful memory performance.

SCHOOL-AGED CHILDREN

Similar to studies in adults, ERP studies in school-aged children typically require participants to encode a large number of stimuli (visual or auditory) and after a short delay (minutes) make judgments about items. However, in contrast to adult research, these judgments tend to only be objective in nature (e.g., asking participants to make old/new and/or source judgments). For example, Cycowicz and colleagues (2003) used ERPs recorded at midline leads to examine source memory in 10- and 12-year-old children and adults. When participants were asked to make old/new judgments, similar ERP patterns were observed across the age groups. However, when participants were asked to make source judgments (regarding the original color of the items), behavioral performance improved with age and was accompanied by different patterns of brain potentials. Although both memory judgments were accompanied by a parietal EM effect (mean amplitude at approximately 500 msec post-stimulus onset, old > new, source-correct > new), source memory judgments were also accompanied by a later frontal EM effect that differentiated items with correct source judgments from those with incorrect source judgments. This effect was apparent at all sites for the adult group but only at frontal sites for the children and adolescents. This latter EM effect showed age-related changes that were associated with improvements in memory performance, suggesting that although school-aged children were able to recollect contextual details, this ability (and its ERP correlate) showed prolonged development during late childhood/adolescence. The authors concluded that their results implicated immaturity of frontal lobe structures in children's difficulty in retrieving source information.

Czernochowski and colleagues (2005) also used ERPs to examine memory for items and their source (whether they were originally encountered as words or photographs) in school-aged children (6–12 years) and adults. The three EM effects commonly found in adult participants were observed for the adult group (early frontal old/new effect, left parietal recollection effect, and a late frontal recollection effect; see above). In contrast, older children and a subgroup of younger children with comparable performance levels showed a single EM effect over left parietal leads (700–1,000 msec) that differentiated between source-correct and source-incorrect responses (i.e., a "recollection effect"). These results were taken to suggest that children rely predominantly on recollection during recognition judgments.

Subsequent investigations by this group have replicated this finding using a continuous recognition memory paradigm (Sprondel et al., 2011). The authors suggest that the finding of reliance on recollection is driven in part by the nature of the task, which requires retrieval of highly familiar items after relatively short delays (Sprondel et al., 2011). When different tasks are used that preferentially engage familiarity process, an early (300–450 msec) old/new EM effect has been identified in 8- to 10-year-old children (e.g., Mecklinger et al., 2011).

PRESCHOOL CHILDREN

To date, very few ERP studies of memory have been conducted in preschool children. In contrast to ERP studies in adults and school-aged children, studies that have been done focus largely on different responses to old versus new stimuli and have not compared responses to different categories of old stimuli (e.g., source-correct vs. incorrect). In addition, due to the limited attentional capacities of children, fewer stimuli tend to be presented during the session and the stimuli that are seen tend to remain on the screen for longer durations. Finally, due to poorer control of body movements, button press responses are not typically used and children are asked to give a verbal response or no response at all. It is also notable that data loss rates (in terms of trials and number of subjects contributing useable data) are much higher in these samples (see DeBoer et al., 2005).

Marshall and colleagues (2002) conducted the first memory ERP study in 4-year-old children. They examined memory for pictures and compared ERP responses of children and adults. During retrieval participants were simply asked to judge verbally (i.e., "yes" or "no") whether they had seen a stimulus previously (old/new judgment). Both children and adults generated more positive ERP responses to old compared to new stimuli. However, in adults these differences in amplitude were observed as early as 450 msec after stimulus onset and extended up until 1,350 msec over both hemispheres. In children, differences were primarily observed 900 to 1,500 msec and showed a tendency to be stronger over the right versus the left hemisphere. The authors concluded that although recognition memory could be indexed using ERPs in preschool children, these responses differed from that in adults in terms of laterality and latency.

Riggins and colleagues (2009a, 2009b) also examined memory using ERPs in 3- and 4-year-old children. In this paradigm, children were introduced to 9-item event sequences 1 week prior to ERP recording. During ERP recording, children passively viewed pictures of items from the familiar event sequences and pictures of items from new sequences they had not seen previously. Following ERP recording, children were asked to behaviorally recall the event-sequences and two measures of behavioral memory were obtained: memory for individual actions (max = 9 per sequence) and memory for actions in the correct temporal order (max = 8 per sequence). ERPs to old and new events were compared and, similar to Marshall et al. (2002), EM effects were observed in the right hemisphere between 900- to 1,500-msec. Although the magnitude of the effect was similar to the Marshall, Drummey, Fox, and Newcombe (2002) study, the direction of the effect differed with greater amplitude to the new in comparison to the old stimuli. This difference may have been due to a number of methodological differences including, (1) whether the information was recalled immediately after encoding, (2) the length of the delay (5 min versus 1 week), (3) the requirements during the ERP recording (verbal response versus passive viewing), and (4) the type of novel items used (trial unique versus repeated items; see Riggins et al., 2009b for discussion). Correlations between behavioral recall and amplitude of the ERP response were examined and showed that memory for individual actions correlated with amplitude in the early time window (400–600 msec) and memory for temporal order correlated with amplitude in the later time window (900–1,500 msec). The authors suggested this pattern of results was consistent with that in school-aged children and adults since item memory effects preceded context memory effects. However, because this temporal order memory paradigm did not allow for back-sorting of trials based on behavioral performance, direct comparisons could not be made between items for which temporal order was correctly recalled versus incorrectly recalled, as is the case in studies with older age groups.

INFANTS

Similar to studies in preschool children, ERP studies of memory in infants have focused exclusively on different responses to old versus new stimuli and have not compared responses to different categories of old stimuli (e.g., source-correct vs. incorrect). Due to attentional and cognitive differences, there are many notable differences in the paradigms used with infants than older age groups. First, no instructions are given to participants during electroencephalogram (EEG) recording. Instead, participants always passively view (or listen to) stimuli. Second, in studies where behavioral responses are collected, these tend to be done prior to or after EEG recording (cf. Reynolds, Courage, & Richards, 2010). It is also common for encoding and retrieval sessions to be separated by a day or more in time as sessions that try to obtain measures of both tend to be too long for infants. Also, because of infants' limited attention span and the difficulty associated with collecting ERP data, this measure is typically only recorded during encoding or retrieval (although there are novel exceptions; see Bauer, Wiebe, Carver, Waters, & Nelson, 2003).

For example, Carver, Bauer, and Nelson (2000) examined memory for novel event sequences in 9-month-old infants using a modified elicited imitation procedure. Specifically, infants participated in a behavioral encoding session on three different days (ranging from 24–72 hours apart) during which they were given brief exposures to three different 2-item action sequences. One week after the last exposure session, ERPs were recorded to pictures of one old and one new event sequence. Finally, behavioral recall for the event sequences was assessed 1 month after the ERP session. ERP responses to old and new stimuli were then compared between infants who recalled the temporal order of the event sequence after the 1-month delay, and those who did not. Only the former showed differential ERP responses to old and new stimuli in early (260–870 msec) and late (870–1,700 msec) windows.

Subsequent studies by this group have gone on to show that despite the fact that the ERP data were collected during passive viewing, the magnitude of these EM effects predicted performance on behavioral measures of temporal order recall of event sequences assessed after ERP data collection (Bauer et al., 2003; 2006).

In general, findings from infant memory paradigms reveal two components that differentiate between old and new stimuli (i.e., show EM effects): the negative component (Nc) and slow wave activity. The Nc is a negative-amplitude component that occurs 400–600 msec after stimulus onset and is maximal over frontal-central leads. This component has been related to obligatory attention in infancy (Nelson & Collins, 1991) and is modulated by memory (Bauer et al., 2003; Carver et al., 2000). The cortical source of Nc has been located in areas of prefrontal cortex and anterior cingulate cortex (Reynolds & Richards, 2005). Slow wave activity begins later (600–900 msec after stimulus onset), does not have a distinct peak, and is more widely distributed across the scalp. Slow wave activity can be either positive or negative in amplitude. Negative slow wave (NSW) has been related to novelty detection, whereas positive slow wave (PSW) has been interpreted as indexing the updating of a partially encoded stimulus or context in working memory (Nelson, 1994; Nelson, Thomas, de Haan, & Wewerka, 1998, see DeBoer et al., 2007 and de Haan 2007 for review). The cortical source of PSW is thought to be in temporal cortical areas (Reynolds & Richards, 2005). Finally, because of this wide distribution, often the dependent measure is area under the curve, as opposed to peak amplitude (which tends to be the dependent measure for other components at all other ages).

PRESENT STUDY

To summarize, ERPs have been used to examine memory in participants ranging in age from infancy to adulthood. In adults and school-aged children two types of EM effects have been identified, old/new effects and recollection effects. Developmental changes have been reported in both components, reflecting improvements in behavioral performance. In preschool children and infants only old/new effects have been reported. It remains unknown whether recollection effects exist due to significant differences in (1) theoretical background, (2) paradigms used (remember/know, source memory, item memory), and (3) methodological details (passive-viewing, when behavioral responses are recorded, length of the delay between encoding and retrieval, whether EEG are recorded during both encoding and retrieval, the number of stimuli used, amount of data lost, etc.). In addition, although only briefly alluded to above, the overall morphology of the electrophysiological response varies substantially from infancy to adulthood (see DeBoer et al., 2005). These differences often require that analyses be conducted on different time windows or components and, sometimes, require the use of different dependent measures (peak amplitude and latency or mean amplitude versus area under the curve).

Thus, the aim of the present report was to determine if recollection EM effects could be detected in the ERP response during early childhood. Behavioral research in children suggests that source memory follows a prolonged developmental trajectory, with significant age-related changes occurring on many laboratory-based paradigms between 4 and 6 years of age (Drummey & Newcombe, 2002; Lloyd, Doydum, & Newcombe, 2009; Sluzenski, Newcombe, & Kovacs, 2006). In this article we describe results from a novel source memory ERP paradigm in 5-year-old children that combines features of those used with older children and infants. The long-term goal of this research is to connect ERP memory literature in infancy and early childhood to ERP memory literature in school-aged children and adults. Many features of the paradigm described below were selected to reflect this long-term goal (i.e., we sought to develop a paradigm that could be used with children younger than the sample reported here). Specifically, we utilized a passive viewing paradigm but collected measures of both item and source memory immediately after EEG recording, which would allow us to back-sort the ERP data and examine both old/new and recollection effects in a manner similar to studies with school-aged children and adults. Thus, the task is appropriate for young children yet includes essential variables for a variety of analyses commonly used in research with older children and adults. We used a 1-week delay (similar to infant studies) because we were specifically interested in long-term recall and engaging both recollective and familiarity processes (see Sprondel et al., 2011). Based on the morphology observed, windows selected for ERP analyses were closer to those found in infants and early childhood, yet the analyses used measures of average amplitude within these windows similar to studies with older subjects. Based on previous work in infants and young children (Bauer et al., 2003; Marshall et al., 2002; Riggins et al., 2009a, 2009b), we predicted EM effects in both early and late windows; however, whether these effects would differentiate source-correct from source-incorrect and new items (i.e., a recollection effect) was unknown.

METHOD

Participants

A total of 49 children participated in the study. Of these, one child was excluded due to a diagnosis of fetal alcohol syndrome that was discovered after the testing session and one child did not return for the second visit. Thus, 47 children (24 male, 23 female) between the ages of 5 and 6 years (mean = 5.61 years, range 5.03 to 6.43) provided behavioral data. Of these children, 39 also provided useable ERP data (2 refused to complete procedure, 1 experienced equipment failure, 5 had poor data quality—e.g., excessive alpha activity that obscured the components of interest). Seven additional children were excluded from the ERP analyses due to performance below chance (i.e., 50%) on the source memory paradigm (see Marshall et al., 2002 for similar approach). Thus, the final sample consisted of 32 (17 female, 15 male, mean age = 5.64 years, range 5.04–6.43 years) participants.[1]

[1]At the request of reviews for a different journal, a sample of adults was also tested on this paradigm. However, behavioral performance was quite low suggesting adults were not engaged in the child-appropriate task. Given the goal of this study was to examine relations between source memory and ERPs in children, data from the adult sample is not included.

Materials

Behavioral stimuli consisted of 90 age-appropriate toys purchased from local stores. Sixty of the items were presented at both visits and an additional 30 were presented as novel items at the second visit (see *Procedure* below). ERP stimuli consisted of 4.5″ × 8″ digital color photographs of the behavioral stimuli.

Procedure

All procedures were approved by the University's Institutional Review Board prior to data collection. Participants were recruited from a database maintained by the University's Infant and Child Studies program. Parents provided informed consent for their children. Children received a small toy and a certificate for their participation.

Children made two visits to the lab, approximately a week apart (mean delay = 6.77 days, range = 5–9 days). At the first visit, each child was shown 60 study items. Although encoding was incidental (i.e., they were not instructed to remember the items) they were instructed to interact with the item in a manner similar to the experimenter to ensure attention was paid to each item and that each item was encoded. The items were divided into 2 sets of 30 items. Each set was shown in a different context that consisted of two rooms designed to be child-friendly and engaging. In addition, these "room-like" contexts provided high ecological validity as such settings are similar to those in which children form memories (e.g., events that occurred at their house versus their school). Each room had a stuffed doll "character" associated with it in order to increase the salience of the context for the child. An experimenter showed the child each item one at a time, related the item to the character, and performed an action associated with the item, which the child was instructed to imitate. The order of the contexts was counterbalanced between participants. Items were matched across contexts (such that both contexts contained items from similar categories, e.g., hats, sports equipment, books). Items were grouped into six subsets of five and the presentation order of these subsets was matched across contexts. Item presentation within sets was random.

At the second laboratory visit, children first participated in the ERP portion of the experiment. Children were fitted with an appropriate size electrode cap and seated in front of a computer screen. They were told that they would see pictures of items they interacted with at the previous session and pictures of new items. Pictures of the "characters" from each room were displayed to remind the child of the experience. Pictures of the two rooms were not displayed. Children were instructed to remain as still as possible and to watch the pictures on the screen (i.e., no overt behavioral response was required). This passive viewing paradigm was used to minimize movement artifact that is associated with behavioral responses such as a button press (DeBoer et al., 2005). ERP trials were back-sorted based on subsequent behavioral performance in the source memory paradigm (see below). The fixed presentation order of the ERP and behavioral task was necessary because the constraints of ERP methodology are such that behavioral recall cannot be done simultaneously, and behavioral testing could influence the ERP response (e.g., by giving children experience with the novel stimuli). Prior research has demonstrated no effect of ERP exposure on subsequent recall performance (Bauer et al., 2003; Carver et al., 2000).

ERPs were recorded from 64 scalp locations, left and right mastoids, two vertical electrooculogram (EOG) and two horizontal EOG channels using active Ag–AgCl electrodes (BioSemi Active 2) while children viewed the stimuli. EEG was recorded at a sampling rate of 512 Hz. Stimuli were presented on the screen for 500 msec, followed by a fixation cross that varied in duration from 1,250 to 1,700 msec. Children viewed the stimuli during two separate blocks. Each block consisted of random presentation of the 60 previously seen (target items) and 30 new (distracter) items, for a total of 180 ERP trials. Two blocks were used because during pilot testing we found this strategy was more effective than doubling the number of to-be-remembered items, which significantly decreased memory performance.

Following ERP data collection, children participated in a source memory paradigm. Children were presented with the 60 target items they had seen on their first visit as well as 30 novel distracter items. Items were presented one at a time and the children were asked to make a judgment as to whether they had seen the item on their first visit or not. If an item was identified as having been seen the week before (i.e., "old"), children were asked to place the item into the context in which they had encountered it on their first visit. If the children reported that they had not seen the item on the previous visit (i.e., "new"), they were asked to place the item into a "new item" bin. In addition to age-appropriate instructions, five training trials were administered to ensure all children understood the task.

Data Reduction and Analyses

For the source memory task, correctly identified target items that were sorted to the correct context are referred to as "source-correct" and are thought to index recollective processes. Correctly identified target items that were sorted to the incorrect context are referred to as "source-incorrect" and are thought to index familiarity processes. Incorrectly identified target items that were judged as new are referred to as "misses." Correctly identified distracter items are referred to as "correct rejections."

Electrophysiological data were re-referenced offline to mathematically linked mastoids using Brain Electrical Source Analysis (BESA) software (MEGIS Software GmbH, Gräfelfing, Germany). Missing data from individual channels was interpolated for a maximum of 10% of bad channels (i.e., six per participant; see DeBoer et al., 2005). Consistent with previous ERP studies in children (Cycowicz et al., 2003; Marshall et al., 2002) ocular artifacts were corrected by applying the Ille, Berg, and Scherg (2002) algorithm. Data were high pass filtered at 0.1 Hz and low pass filtered at 80 Hz. Movement related artifacts were hand-edited and rejected prior to averaging. Trials were epoched with a 100 msec baseline and continued during stimulus presentation for 1,500 msec. ERPs were averaged based on behavioral performance as described above for the source-correct, source-incorrect, and correct rejection conditions. Participants with fewer than 10 trials per condition were excluded from analysis. Mean trial numbers (range) were: source-correct 41 (18–67), source-incorrect 26 (13–39), and correct rejection 31 (14–52).

Differences between ERP responses to source-correct versus both source-incorrect and correct rejections (new items) indicate an EM effect that is sensitive to recollection (referred to as a recollection effect), whereas an EM effect that differs between source-correct/source-incorrect and correct rejections is sensitive to recognition in general (referred to as an old–new effect).

The resulting waveforms contained two components closely resembling the Nc and the positive slow wave (PSW), which have been previously identified in developmental ERP memory literature (e.g., Bauer et al., 2003; Marshall et al., 2002; for review see de Haan, 2007) and were discussed in the Introduction. Based on these previous studies and visual inspection of the data two windows were selected for ERP analysis: 350–500 msec and 800–1,500 msec. Average amplitude was used as the dependent measure.

Repeated measures (RM) ANOVAs were conducted for six midline leads with the following factors: 6 Coronal Plane (antero-frontal, frontal, fronto-central, central, central-parietal, parietal) $\times$ 3 Condition (source-correct, source-incorrect, correct rejection) and 24 lateral leads with the following factors: 2 Hemisphere (left, right) $\times$ 2 Sagittal Plane (medial, lateral) $\times$ 6 Coronal Plane (antero-frontal, frontal, fronto-central, central, central-parietal, parietal), $\times$ 3 Condition (source-correct, source-incorrect, correct rejection) included the following leads: AF3, AF4, AF7, AF8, F1, F2, F3, F4, FC1, FC2, FC3, FC4, C1, C2, C3, C4, CP1, CP2, CP3 CP4, P1, P2, P3, P4. Greenhouse-Geisser corrections for non-sphericity were used when necessary. Only significant effects with condition are reported.

RESULTS

Behavioral Performance

Children correctly identified an average of 87% of items as "old" (*SD* = 7%, range = 68–100%). Of these "old" items, children correctly identified the context for 58% (*SD* = 9%, range = 44–77%), which was significantly greater than chance, $t(47) = 6.84$, $p < .001$. Children correctly identified an average of 83% of the new items as new (*SD* = 13%, range = 43–100%). There were no behavioral differences for the subset of 32 children included in the ERP analysis.

ERP Data

Grand average waveforms are depicted in Figure 1. ERP results are presented for each window separately; midline leads are discussed first followed by lateral leads.

Early window: 350–500 msec. Analysis of midline leads showed a marginal effect of Condition, $F(2,62) = 2.80$, $p = .07$. Means and standard errors were: source-correct: –20.19 μV (.93 μV), source-incorrect: –21.18 μV (.89 μV) and correct rejection: –22.37 μV (1.13 μV), with no significant pairwise comparisons. Analysis of lateral leads revealed a main effect of Condition, $F(2,62) = 3.58$, $p < .05$. Average amplitude to source-correct differed from correct rejections, $p = .05$, whereas amplitude to source-incorrect did not differ from either one, see Figure 2.

Late window: 800–1,500 msec. Analysis of midline leads showed a main effect of Condition, $F(2,62) = 7.91$, $p = .001$. Average amplitude to both source-correct items (mean = 9.42 μV, SE = .67 μV) and source-incorrect items (mean = 8.37 μV, SE = .72 μV) differed from correct rejections (mean = 6.62 μV, SE = .62 μV), *p*s < .05. Analysis of lateral leads also revealed a main effect of Condition, $F(2,62) = 9.38$, $p < .001$, which was qualified by an interaction among Condition, Coronal Plane, and Sagittal Plane, $F(10, 310) = 2.08$, $p = .05$. Follow-up

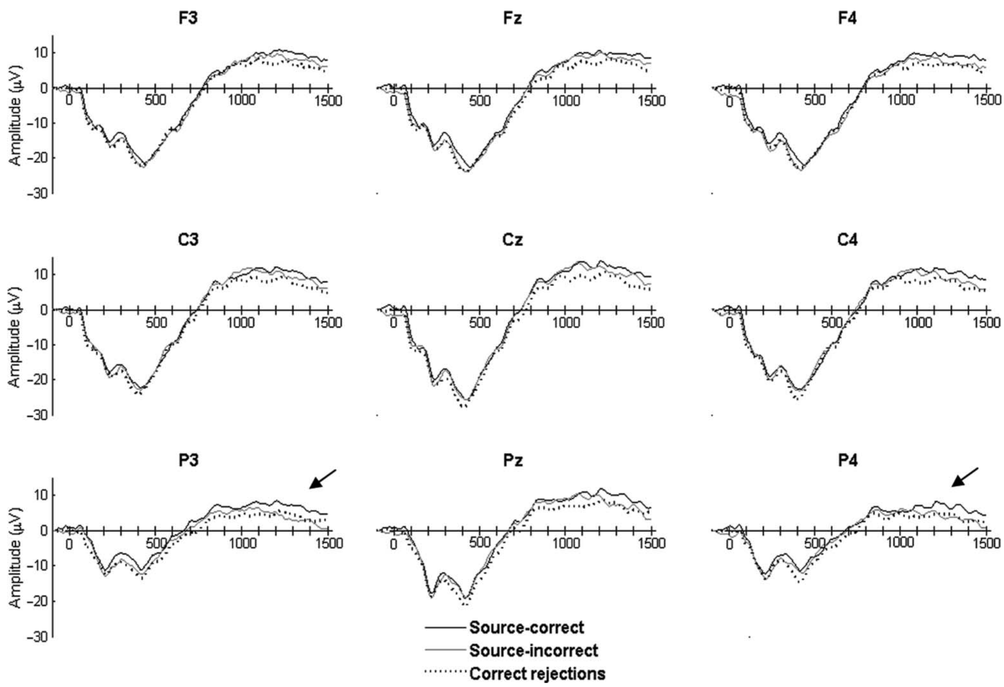

FIGURE 1 Grand average waveforms for source-correct, source-incorrect, and correctly rejected stimuli.

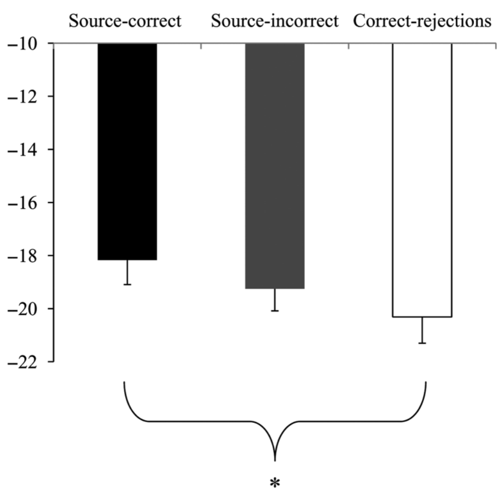

FIGURE 2 Average amplitude to source-correct, source-incorrect, and correctly rejected stimuli in the early latency window (350–500 ms) at lateral leads, $^{*}p < .05$.

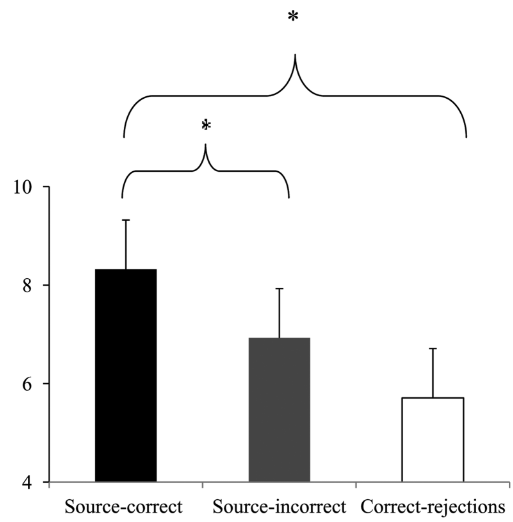

FIGURE 3 Average amplitude to source-correct, source-incorrect, and correctly rejected stimuli in the late latency window (800–1500 ms) at temporal lateral leads, $^{*}p < .05$.

analyses for each Sagittal Plane identified main effects of Condition at both temporal, $F(2, 62) = 9.41$, $p < .001$, and medial, $F(2, 62) = 8.98$, $p < .001$, leads. At temporal leads, average amplitude to source-correct items differed from both source-incorrect and correct rejections which did not differ from each other, *p*s < .05, see Figure 3. At medial leads, average amplitude to source-correct items (mean = 9.03 μV, SE = .59 μV) differed from correct rejections (mean = 6.29 μV, SE = .64 μV), $p = .001$, whereas amplitude to source-incorrect (mean = 7.85 μV, SE = .69 μV) did not differ from either one.

Correlations Between Behavioral Measures and ERPs

In order to explore the association between behavioral performance on the source memory task and ERP responses, we examined relations between percent correct for both item and source memory and average amplitude in both the early and late ERP windows. To reduce the number of correlations, data from individual leads were averaged to create variables for temporal and medial regions in each hemisphere that were revealed to be separate regions of interest by the results of the repeated measures analyses presented above (i.e., a left temporal region including AF7, F3, FC3, C3, CP3, P3, a right temporal region including AF8, F4, FC4, C4, CP4, P4, a left medial region including AF3, F1, FC1, C1, CP1, P1, a right temporal region including AF4, F2, FC2, C2, CP2, P2). To control for individual differences in overall amplitude, average amplitude to source-correct items was adjusted for each participant by subtracting average amplitude to correctly rejected items. All 39 participants who provided useable ERP data were included in this analysis to maximize variability.

A significant association was found between average amplitude the left temporal region and source memory performance, $r(39) = .31$, $p = .05$. Greater amplitude to source-correct compared

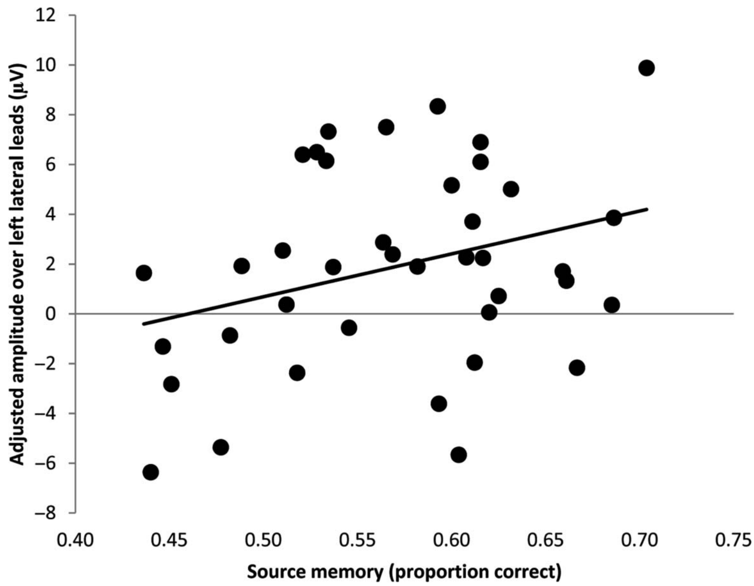

FIGURE 4 Relation between slow wave activity in left temporal lateral region (source-correct minus correct rejections) and source memory performance.

to correct rejections was related to better performance on the source memory task (Figure 4). No significant associations were found for item memory or for the early time window.

DISCUSSION

The present study examined EM effects in 5-year-old children using a novel source memory paradigm. Results revealed a recollection effect in the late time window (800–1,500 msec after stimulus onset). Specifically, activity over lateral leads distinguished items with source-correct responses from both source-incorrect responses and correct rejections. This pattern of results is similar to effects observed in adults 420–490 msec after stimulus onset that extend for several hundred milliseconds over left parietal regions. The distribution of this component was different from that observed in adults; in children this effect was observed in both hemispheres and was distributed across the entire scalp. In adults recollection effects are localized to left parietal regions. This pattern of increasing localization with age is consistent with previous reports of increased spatial specificity of ERP effects with age found in language processing (Mills, Coffey-Corina, & Neville, 1997), face processing (Halit, de Haan, & Johnson, 2003), and developmental theories that suggest a shift from diffuse to focal cortical activity with development (Durston et al., 2006).

The timing of this effect is similar in both children and adults in that it occurs later in the waveform (albeit much later in children). In addition, similar to the recollection effect in adults, in our child sample, amplitude to source-correct items was related to retrieval success. Although the repeated measures ANOVA analyses suggested a bilateral effect, this correlation was only observed over leads in the left hemisphere, perhaps reflecting an early indicator of lateralization consistent with findings in adult subjects. These findings suggest positive slow wave activity may reflect recollective processes in a manner similar to the left parietal effect in adults. This interpretation is consistent with previous literature in infants, which suggests activity in this time window is generated by sources within the temporal lobe. However, this was an initial study and additional research is necessary to support this claim.

In comparison, in the early time window (350–500 msec), a more graded effect was observed. Although activity in lateral leads distinguished source-correct items from correct rejections, source-incorrect items fell in between. This finding differs from EM effects observed in adults in that it does not reflect familiarity or recollection per se. Instead, this pattern of results may reflect the strength of the memory trace (e.g., stronger versus weaker memories, see Wixted, 2007). This interpretation is consistent with previous literature in infants, which suggests activity in this time window is related to obligatory attention that is modulated by memory and localized to the anterior cingulate. In this sense, amplitude early in the child waveform does not distinguish between memory processes but can index the strength of the memory trace via its effect on attention.

Similar to studies in school-aged children (i.e., Cycowicz et al., 2003; Czernochowski et al., 2005; Mecklinger et al., 2011; Sprondel et al., 2011) our findings reveal a component reflecting recollection, but no component reflecting familiarity. These findings may suggest that children rely more extensively on recollection (counter to behavioral work, Drummey & Newcombe, 2002; Lloyd, Newcombe, & Doydum, 2009; Sluzenski et al., 2006) or it is possible that the features of this task (e.g., the 1-week delay) mask familiarity effects by preferentially tapping recollection. Future research varying task demands in a manner that would engage familiarity processes needs to be conducted to tease apart these possibilities.

The results of the present study are exciting because they suggest paradigms used with older children and adults to examine the development of dual memory processes (recollection and familiarity) can be modified and extended to include younger ages. This is important not only for knowledge regarding the development of memory but also such work will begin to bridge the gap between infant ERP literature and ERP literature in older children and adults. However, this is the first attempt and additional studies must be conducted if real progress is to be made. In addition to the suggestions above, future research also needs to examine the effects of using passive-viewing versus active paradigms during ERP recording determine if differences exist between recording behavioral responses concurrently as opposed to after ERP recording. In addition, questions that remain include at what point in development can recollection and familiarity be detected, whether they develop over time out of a more undifferentiated form of memory or exist separately beginning at birth, and if the parameters of each are similar to those observed in adults (e.g., is recollection slower than familiarity; is recollection subserved by the hippocampus and left PFC; Brainerd et al., 2009; Newcombe & Crawley, 2007). Addressing these questions is essential for bridging the current gap between what is known about memory in adults and how it develops. Finally, longitudinal studies should be conducted examining changes in ERP morphology to ascertain whether the negative component and slow wave activity observed in studies with children are analogous to the Nc and slow waves in infants.

In summary, findings from this study suggest that recollection EM effects can be detected in the ERP response during early childhood. This is particularly exciting because behavioral research suggests that source memory shows significant age-related changes between 4 and

6 years of age (Drummey & Newcombe, 2002; Lloyd et al., 2009; Sluzenski et al., 2006). The novel source memory ERP paradigm used in the present report combined features of ERP paradigms used with older children/adults and infants. This study is an important first step towards a long-term goal of connecting ERP memory literature in infancy and early childhood to ERP memory literature in school-aged children and adults.

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