Age-Related Differences in Subjective Recollection: ERP Studies of Memory Encoding and Retrieval

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Highlights

- Children can reliably make subjective memory judgments, although this ability improves with age
- Age-related differences were present in ERP effects associated with recollection at retrieval, but not encoding
- A recollection ERP effect at retrieval was absent in children, widespread in adolescents, and more spatially-localized in adults
- These findings suggest that age-related differences in recollection may be primarily due to the development of post-encoding processes

Abstract

The ability to mentally re-experience past events improves significantly from childhood to young adulthood; however, the mechanisms underlying this ability remain poorly understood, partially because different tasks are used across the lifespan. This study was designed to address this gap by assessing the development of event-related potential (ERP) correlates associated with subjective indices of recollection. Children, adolescents, and adults performed Tulving's (1985) remember/know paradigm while ERPs were recorded during memory encoding (Experiment 1) and retrieval (Experiment 2). Behaviorally, children recognized fewer items than adolescents and adults. All age groups reliably made subjective judgments of recollection, although the ability to make these judgments improved with age. At encoding, the ERP effect associated with recollection was present and comparable across age groups. In contrast, the ERP effect associated with recollection at retrieval differed as a function of age group; specifically, this effect absent in children, topographically widespread in adolescents, and, consistent with previous literature (Friedman & Johnson, 2000), maximal over left centro-parietal leads in adults. These findings suggest that encoding processes associated with the subsequent subjective experience of recollection may be similar among children, adolescents, and adults and that age-related improvement in recollection may be primarily attributable to the development of processes that follow the initial encoding of stimuli (i.e., consolidation, storage, retrieval).

Keywords: memory; recollection; event-related potentials; encoding; retrieval; remember/know paradigm

Age-Related Differences in Subjective Recollection: ERP Studies of Memory Encoding and Retrieval

The ability to recollect contextual details associated with events develops into adolescence (for review see Ghetti & Bunge, 2012); however, the neural mechanisms underlying the development of recollection are not well understood, partially because different tasks are used across the lifespan. The aim of the present study was to contribute to this gap in the literature by examining the development of event-related potential (ERP) correlates associated with recollection during memory encoding and retrieval in children, adolescents, and adults using Tulving's (1985) remember/know paradigm.

Research in adults across multiple methodologies predominantly measures recollection subjectively, using measures such as the receiver operating characteristic (ROC) procedure (Yonelinas, 1994) and Tulving's (1985) remember/know paradigm (for review of recollection research in adults see Yonelinas, 2002). ROCs relate the proportion of correctly and falsely recognized items to a subjective criterion, such as memory confidence. During the remember/know paradigm participants encode stimuli (e.g., pictures or words) and, at retrieval, identify whether they *remember* contextual information associated with each stimulus (e.g., what they thought of or how they felt when they saw the stimulus) or if they merely *know* they previously encountered the stimulus. The remember/know paradigm has been used extensively in ERP studies of adults to examine the neural bases of recollection (for review see Friedman & Johnson, 2000). The subsequent memory effect at encoding is characterized by subsequently remembered items eliciting a more positive amplitude ERP response than items subsequently identified as familiar and missed items. The subsequent memory effect is widespread over the scalp and present 400-1000 ms poststimulus onset (e.g., Duarte, Ranganath, Winward, Hayward,

& Knight, 2004; Friedman & Trott, 2000; Mangels, Picton, & Craik, 2001; Yovel & Paller, 2004). Consistent with the subsequent memory effect at encoding, the recollection effect at retrieval is characterized by remembered items eliciting a more positive amplitude ERP response than familiar and correctly rejected novel items. This effect is focused over left parietal leads 400-800 ms poststimulus onset (for reviews see Friedman & Johnson, 2000; Rugg & Curran, 2007).

Developmental research on recollection suggests that memory for contextual information improves into adolescence. Most behavioral paradigms used in developmental research measure recollection objectively, by asking participants to identify a contextual detail from encoding, such as item color (e.g., Cycowicz et al., 2003; Ghetti, DeMaster, Yonelinas, & Bunge, 2010), background picture (e.g., Lloyd, Doydum, & Newcombe, 2009), or study context (e.g., Czernochowski et al., 2005; Riggins & Rollins, 2015; Riggins et al., 2013; Rollins & Riggins, 2013). Due to concerns about children's ability to understand introspective tasks (Brainerd, Holliday, & Reyna, 2004; Brainerd, Payne, Wright, & Reyna, 2003; Ghetti, Qin, & Goodman, 2002), relatively fewer studies of children have indexed recollection subjectively using the ROC procedure (Ghetti & Angelini, 2008) and remember/know paradigm (Billingsley, Smith, & McAndrews, 2002; Friedman, de Chastelaine, Nessler, & Malcolm, 2010; Ghetti, Mirandola, Angelini, Cornoldi, & Ciaramelli, 2011; Hembacher & Ghetti, 2013; Ofen et al., 2007; Piolino et al., 2007). However, a recent study demonstrated that children as young as 6 years can reliably make remember/know judgments (Ghetti et al., 2011) and thus set the foundation for studies to examine the neural bases of recollection using the remember/know paradigm.

ERP Studies of Recollection in Children

ERP studies of recollection in children have exclusively examined the neural bases of recollection with objective paradigms (e.g., Cycowicz, Friedman, & Duff, 2003; Czernochowski, Mecklinger, & Johansson, 2009; Czernochowski, Mecklinger, Johansson, & Brinkmann, 2005; Mecklinger, Brunnemann, & Kipp, 2011; Riggins & Rollins, 2015; Riggins, Rollins, & Graham, 2013; Rollins & Riggins, 2013; Sprondel, Kipp, & Mecklinger, 2011, 2012). Only one of these studies has assessed whether ERPs recorded during *encoding* are related to recollection in children (Rollins & Riggins, 2013). Rollins and Riggins (2013) found that ERPs did not differentiate context-correct items from context-incorrect and missed items in either children or adults (i.e., ERPs at encoding were not associated with recollection). This finding is consistent with previous research with adults suggesting that the subsequent recollection effect is more robust when recollection is indexed subjectively (Duarte et al., 2004; Friedman & Trott, 2000). It is possible that utilizing a subjective index of recollection will elucidate age-related differences in the subsequent recollection effect.

Developmental ERP studies of *retrieval* suggest changes in memory with age (Cycowicz et al., 2003; Czernochowski et al., 2009; Czernochowski et al., 2005; Mecklinger et al., 2011; Riggins & Rollins, 2015; Sprondel et al., 2011, 2012). However, research is inconsistent about whether retrieval processes associated with recollection develop with age. One study suggested that the parietal old/new effect associated with recollection develops during childhood (Cycowicz et al., 2003); however, other studies have shown that children, like adults, show the parietal old/new effect but not an earlier occurring frontal effect associated with familiarity (Czernochowski et al., 2005; Friedman et al., 2010; Sprondel et al., 2011). Additional research is needed to reconcile these differences across studies and identify whether the parietal old/new effect that is associated with recollection differs as a function of age when recollection is indexed subjectively.

Current Study

The aim of the current study was to further knowledge on the development of recollection by examining ERP correlates of recollection at encoding and retrieval in children, adolescents, and adults using Tulving's (1985) remember/know paradigm. A main strength of this research is the use of the remember/know paradigm across a wide age range. Objective paradigms are problematic because 1) the accurate identification of a contextual detail is not necessarily accompanied by recollection (e.g., could be due to guessing) and 2) the failure to accurately identify the detail in an objective paradigm does not mean that other contextual details were not recollected (i.e., noncriterial recollection, Yonelinas & Jacoby, 1996). Further, there is evidence of a partial dissociation between neural regions that support performance on objective and subjective measures of recollection (Duarte, Hensen, & Graham, 2008). A second advantage of the present study is that data are reported from encoding and retrieval because developmental changes in memory from childhood through adulthood may be due to encoding, consolidation, storage, or retrieval processes. We hypothesized that, consistent with previous research (for review see Friedman & Johnson, 2000, and Rugg & Curran, 2007), ERP effects at encoding and retrieval would be related to recollection in adults (i.e., the amplitude of the ERP waveform elicited to remembered items would be more positive relative to familiar and missed/novel items). Given previous research, the effect at encoding was expected to occur between 400 and 1000 ms and the effect at retrieval was expected to occur between 400 and 800 ms and be maximal over left centro-parietal leads. Additionally, based on current developmental research (e.g., Cycowicz et al., 2003; Rollins & Riggins, 2013), we hypothesized age-related differences in ERP effects associated with recollection at encoding and retrieval; specifically, younger age groups would either not demonstrate a recollection effect or that the effect would occur later or be more topographically widespread relative to older age groups.

Method

Two separate experiments were conducted to investigate the development of ERP responses associated with recollection as indexed by the remember/know paradigm (Tulving, 1985) at encoding (Experiment 1) and retrieval (Experiment 2). Separate experiments were necessary because EEG data quality, especially in children, is negatively influenced by longer recording durations. The materials, procedure, and analyses were as similar as possible across experiments.

Participants

For Experiment 1, 17 children (mean age = 7.84 years, *SD* = 0.7, 10 females, 7 males), 24 adolescents (mean age = 12.86 years, *SD* = 0.63, 14 females, 10 males), and 25 young adults (mean age = 20.68 years, *SD* = 2.54, 14 females, 11 males) contributed complete behavioral and electrophysiological data. Two adult participants did not provide their exact birthdate; however, they fell within the range of tested participants. For Experiment 2, 20 children (mean age = 7.48 years, *SD* = 0.4, 12 females, 8 males), 19 adolescents (mean age = 12.68 years, *SD* = 0.62, 14 females, 5 males), and 29 young adults (mean age = 19.79 years, *SD* = 1.37, 19 females, 10 males), contributed complete behavioral and electrophysiological data. The majority of the participants self-identified as non-Hispanic Caucasian. Exclusion criteria included self/parent-reports of the following conditions: prematurity (gestational age of < 37 weeks), red-green colorblindness, or a history of neurological, developmental, or learning disorders (child participants were excluded based on parent report of these criteria). Participants were not eligible for Experiment 2 if they had participated in Experiment 1. Participants were recruited from databases maintained by the University. In compensation for their participation, children received a small gift, adolescents received a small gift or $10, and adults received course credit.

Materials

Memory paradigm. Stimuli included 194 images from a colored version of the Snodgrass and Vanderwart line drawings (Rossion & Pourtois, 2004) and external sources. These same stimuli have been used in previous research (Rollins & Riggins, 2013). Fourteen images were used as practice stimuli, and the remaining 180 images were used as task stimuli. The 180 task stimuli were altered to be shades of red or green for the encoding phase and gray for the retrieval phase.

Classification task. The classification task examined understanding of the terms remember and familiar. This task was modeled after the assessment used by Ghetti and colleagues (2011). Participants classified 36 total statements (18 remember, 18 familiar). Six remember statements were associated with memory for each of the following: color, the semantic judgment, and both the color and semantic judgment (e.g., “I saw sunglasses, I can picture them in red and I said they were not living”). Six familiar statements were associated with the absence of memory for color, the semantic judgment, and both the color and the semantic judgment (e.g., “I saw a pelican, but I can’t tell if it was red or green”). Because both recollected and familiar items can be associated with high confidence recognition, 6 remember and 6 familiar statements were high in confidence (e.g., “I definitely saw a panther, but I can’t tell you what question you asked me”).

2.3. Procedure

The procedure was modeled after Ghetti and colleagues (2011) and Rollins and Riggins (2013).

Memory paradigm (Figure 1).

Encoding. Participants were seated in front of a computer screen in a dimly lit room and were aware that their memory would be subsequently examined. Participants viewed 11 practice stimuli and 120 test stimuli at encoding. To allow for the assessment of whether participants were reliably making remember and familiar judgments, participants made a color and a semantic judgment (i.e., animacy or size) for each stimulus (Ghetti et al., 2011). During the practice phase, the experimenter asked the participants to provide verbal responses only once the stimulus was removed from the screen (i.e., to avoid the inclusion of movement artifact during the EEG recording epoch) and instructed the participants on how to make color and semantic judgments for five stimuli. Then, participants practiced making the judgments themselves for six stimuli. During the test phase, participants' semantic judgments about animacy and size alternated in blocks of 30 stimuli (i.e., ABAB) to decrease executive function demands associated with switching (for a similar approach see Rollins & Riggins, 2013, and Ghetti et al., 2011). The semantic judgment made first and the stimulus sets that were associated with each encoding block were counterbalanced across participants. The presentation of individual stimuli within sets was randomly selected by E-Prime 2.0 presentation software (Psychological Software Tools, Inc., Pittsburgh, PA). A fixation cross was displayed on a white background for an inter-trial interval of 500 ms, and stimuli were presented for 1500 ms. Following the stimulus, questions were presented on the screen and remained until the participants made a response (e.g., Red/Green?). The experimenter recorded all participants' verbal responses via a button press to avoid movement-related artifact associated with a button press, especially in younger participants

(DeBoer, Scott, & Nelson, 2005). Between blocks the experimenter reminded participants about the judgments they would be making and that they would subsequently complete a memory task. The encoding phase lasted approximately 15 minutes.

Delay. Participants in both experiments experienced a filled delay to prevent rehearsal. The EEG cap was either removed (Experiment 1) or applied (Experiment 2), and participants conversed with the researchers, watched a movie, or completed paperwork.

Retrieval. At retrieval, participants viewed 9 practice stimuli and 180 test stimuli (120 stimuli previously viewed at encoding and 60 novel stimuli). All stimuli were presented in grayscale at retrieval. Stimuli were presented in a random order using E-Prime 2.0 presentation software (Psychological Software Tools, Inc., Pittsburgh, PA). A 500 ms fixation cross was presented between stimuli, and each stimulus was presented for 1500 ms before participants were prompted to provide memory judgments (ERP data were time-locked to the initial presentation of the stimulus). Participants then made self-paced memory judgments. For each item, participants made a recognition judgment (i.e., Old/New?). Then, for items identified as "Old," a remember/familiar judgment, color judgment, and semantic task judgment (see Figure 1). Consistent with Ghetti and colleagues' study (2011), the color and semantic task judgments were collected to verify that participants were reliably making remember/familiar judgments. Memory judgments were self-paced.

During the practice phase, participants were instructed to make a remember judgment when they could remember a specific detail about the item (e.g., item color) and a familiar judgment when they knew they had seen the item before but were unable to retrieve specific contextual information associated with it. To reduce the likelihood that all high confidence items would receive a remember judgment, participants were told that if they were "very sure" that they had previously seen an item but were unable to remember a specific contextual detail, then the item should receive a familiar response. Following instructions, participants were asked to define the terms remember and familiar, and additional instructions and feedback were provided on the 9 practice items if participants did not demonstrate understanding. All participants demonstrated understanding prior to making the judgments for the 180 test stimuli. The retrieval phase lasted approximately 30 minutes.

Classification task. After the memory task, participants performed the classification task (Ghetti et al., 2011). The experimenter explained that other participants had previously completed a memory study during which they performed the same encoding task (i.e., identified item color and made a semantic judgment regarding animacy or size). However, they had to tell the experimenter what they remembered about the picture at retrieval. The experimenter provided abridged instructions for how a remember/familiar judgment should be made. The experimenter read one practice statement and 36 test statements to the participants and recorded whether the participants thought each statement met the criteria for a remember or familiar judgment. If necessary, the experimenter repeated the statement. Participants were required to perform statistically above chance on the classification task (i.e., according to the binomial distribution, classifying ≥ 24 statements correctly is associated with $p < .05$) to be included in the present report. One child and two adolescents did not meet this criterion for Experiment 1 and three children did not meet this criterion for Experiment 2.

EEG recording. EEG was continuously recorded with a sampling rate of 512 Hz (BioSemi Active 2) from 64 active Ag-AgCl scalp electrodes and two vertical and two horizontal electrooculogram (EOG) channels. For Experiment 1, the EEG cap was applied before participants began the memory paradigm, EEG data were collected during the encoding portion of the study, and the cap was removed between encoding and retrieval. For Experiment 2, the EEG cap was applied between encoding and retrieval, EEG data were collected during the retrieval portion of the study, and the cap was removed following retrieval. Separate experiments were conducted because EEG data quality, especially in children, is negatively influenced by longer recording durations.

EEG Data Processing and Analysis

Data were re-referenced offline using Brain Electrical Source Analysis (BESA) software (MEGIS Software GmbH, Gräfelfing, Germany) to an average mastoid configuration. Consistent with prior ERP studies of memory development (e.g., Cycowicz et al., 2003; Rollins & Riggins, 2013), trials containing ocular artifacts were corrected using the algorithm by Ille, Berg, and Scherg (2002). Data were high and low pass filtered at .1 and 80 Hz for analysis and .1 and 30 Hz for visual presentation. ERPs were epoched with a 100 ms prestimulus baseline and extended to 1500 ms poststimulus onset. Participants were excluded from all analyses due to problems with the reference electrodes or if they contributed fewer than 10 trials per condition due to movement-related artifact or behavioral performance, a requirement that either meets or exceeds recommended and published minimums (Czernochowski et al., 2005; DeBoer et al., 2005; Rollins & Riggins, 2013). The following number of participants did not provide a sufficient number of ERP trials: 35 children (15 from Experiment 1), 10 adolescents (4 from Experiment 1), and 13 adults (5 from Experiment 1).

Analyses were performed using IBM SPSS Statistics 20 (IBM Corp., Chicago, IL). The ERP data analysis strategy was modeled after previous research that utilized the remember/know paradigm in adults (Duarte et al., 2004; Friedman & Trott, 1999; 2000; Mangels et al., 2001). Mean amplitudes were analyzed from each time window (see below for windows) using an omnibus ANOVA with Age Group (children, adolescents, adults) as the between-subjects factor and the following within-subjects factors: 3 Condition x 3 Coronal Plane (frontal, central, parietal) x 3 Sagittal Plane (left, midline, right) at the following leads, F3, Fz, F4, C3, Cz, C4, P3, Pz, P4. The 3 Levels for Condition for Experiment 1 included Remember, Familiar, and Missed items, and the 3 Levels for Condition for Experiment 2 included Remember, Familiar, and Correctly Rejected items. For all ERP analyses, only a main effect of or interaction with Condition is reported since this report is focused on memory effects. The Bonferroni correction was applied to correct for multiple comparisons within analyses, and the Greenhouse Geisser correction was applied to correct for violations of sphericity, which are common in ERP data. An alpha level of .05 was used for all statistical analyses and, when necessary, appropriate follow-up analyses were conducted.

See Table 1 for descriptive statistics associated with trial numbers for each age group, condition, and experiment. Although there were differences in the number of trials between age groups and conditions, mean amplitudes, which were used as the dependent measure of interest, are relatively uninfluenced by differences in trial numbers across conditions, (Luck, 2005). Consistent with previous studies of memory encoding (e.g., Duarte et al., 2004; Rollins & Riggins, 2013), mean amplitudes for Experiment 1 were evaluated for 150-300 ms, 300-450 ms, 500-700 ms, 700-900 ms time windows for children and adolescents and 125-250 ms, 250-350 ms, 500-700 ms, and 700-900 ms time windows for adults. Memory effects from the 700-900 ms time window are reported below. For Experiment 2, two earlier time windows were selected to examine the frontal old/new effect that has been associated with familiarity and two later time windows were selected to examine the parietal old/new effect that has been associated with recollection (see Friedman & Johnson, 2000 for review and Duarte et al., 2004, for similar time windows). Mean amplitudes were evaluated for 150-300 ms, 300-450 ms, 500-700 ms, 700-900 ms time windows for children and 125-250 ms, 250-450 ms, 500-700 ms, and 700-900 ms time windows for adolescents and adults. Memory effects from the 500-700 ms time window are reported below. No significant memory effects were present in the time windows not reported; analyses are available from the corresponding author upon request.

Results

Behavioral Results

Overall, the analysis of behavioral performance across both experiments suggested that children remembered fewer items than adolescents and adults. Critically, although the ability to make remember/know judgments improved with age, all age groups reliably distinguished between remembered and familiar items. Supporting analyses are below.

Age-related differences in item recognition. To determine that all age groups accurately discriminated between studied and novel items, a 2 Experiment (encoding, retrieval) x 3 Age Group (children, adolescents, adults) x 2 Stimulus Type (studied, novel) mixed-model ANOVA was performed with the proportion of "old" judgments as the dependent measure. There was a significant main effect of Stimulus Type, $F(1, 128) = 2209.67$, $p < .01$, $\eta_p^2 = .95$. Studied items ($M = .65$, $SE = .01$) were endorsed as previously encountered more than novel items ($M = .05$, $SE = .01$). There was also a main effect of Age Group, $F(2, 128) = 13.24$, $p < .01$, $\eta_p^2 = .17$. Compared to adolescents ($M = .37$, $SE = .01$) and adults ($M = .38$, $SE = .01$), children ($M = .3$, $SE = .01$) endorsed fewer items as previously encountered. Neither the main effect of nor interactions with Experiment were significant (*ps* > .2).

No age-related differences in rates of remember/familiar responses for previously encountered items. The proportion of items given remember and familiar responses relative to all previously encountered items was examined using a 2 Experiment x 3 Age Group x 2 Subjective Judgment (remember, familiar) mixed-model ANOVA. Consistent with the results above, children overall recognized fewer items as old (i.e., gave fewer remember/familiar responses) than adolescents and adults, $F(2, 128) = 8.17$, $p < .01$, $\eta_p^2 = .11$ (see Figure 2). There was also a main effect of Subjective Judgment, $F(1, 128) = 4.21$, $p = .04$, $\eta_p^2 = .03$. Participants provided previously encountered items with remember judgments more often ($M = .34$, $SE = .01$) than familiar judgments ($M = .3$, $SE = .01$). Neither the main effect of nor interactions with Experiment were significant ($ps > .15$).

Age-related differences in reliable use of remember/familiar responses. Two analyses were conducted to ensure all participants accurately made remember/familiar judgments. First, we analyzed whether falsely recognized novel items were predominantly associated with familiar responses by conducting a 2 Experiment x 3 Age Group x 2 Subjective Judgment mixed-model ANOVA with the rate of falsely recognized novel items as the dependent measure (see Figure 2). Main effects of Age Group, $F(2, 128) = 4.26$, $p = .02$, $\eta_p^2 = .06$, and Subjective Judgment, $F(1, 128) = 19.78$, $p < .01$, $\eta_p^2 = .13$, were qualified by an Age Group x Subjective Judgment interaction, $F(2, 128) = 3.12$, $p = .05$, $\eta_p^2 = .05$. There was neither a main effect of nor interaction with Experiment ($ps > .23$). Critically, follow-up tests conducted separately for each age group showed that children, $t(36) = 2.13$, $p = .04$, $d = .71$, adolescents, $t(42) = 2.38$, $p = .02$, $d = .73$, and adults, $t(53) = 5.41$, $p < .01$, $d = 1.49$, all provided falsely recognized novel items with familiar responses more than remember responses. The interaction emerged because older participants were more likely to provide falsely recognized items with familiar judgments than younger participants (see Figure 2). This suggests that although all age groups made the subjective judgments accurately, understanding improved with age.

Next, we examined whether memory for contextual details associated with studied stimuli was higher when participants provided remember versus familiar judgments. A 2 Experiment x 3 Age Group x 2 Subjective Judgment x 2 Contextual Detail (color, semantic) mixed-model ANOVA was conducted with accuracy for the contextual detail as the dependent measure. The results revealed main effects of Subjective Judgment, $F(1, 128) = 95.15$, $p < .01$, $\eta_p^2 = .43$, and Contextual Detail $F(1, 128) = 101.04$, $p < .01$, $\eta_p^2 = .44$, that were qualified by a Subjective Judgment x Contextual Detail interaction, $F(2, 128) = 4.05$, $p = .05$, $\eta_p^2 = .03$, and an Age Group x Subjective Judgment interaction, $F(2, 128) = 4.83$, $p = .01$, $\eta_p^2 = .07$. No other main effects or interactions were significant (*ps* > .27). First, we examined the Subjective Judgment x Contextual Detail interaction. Accuracy was higher for both the item's color, $t(133) = 6.1$, $p < .01$, $d = 1.06$, and the semantic judgment made at encoding, $t(133) = 9.88$, $p < .01$, $d = 1.71$, when participants made a remember judgment than a familiar judgment. The interaction was present because the accuracy difference between remember and familiar judgments was greater for semantic ($M = .10$, $SE = .01$) than color judgments ($M = .07$, $SE = .01$), $t(133) = 1.99$, $p = .05$, $d = .34$. Follow-up *t*-tests for the Age Group x Subjective Judgment interaction revealed that although accuracy for the contextual detail was higher when children, $t(36) = 3.16$, $p < .01$, $d =1.05$, adolescents, $t(42) = 5.66$, $p < .01$, $d = 1.74$, and adults, $t(53) = 8.93$, $p < .01$, $d = 2.45$, provided remember judgments than familiar judgments, the interaction emerged because with age participants had larger differences in accuracy as a function of subjective judgment (see Figure 3). Consistent with the analysis above, although all age groups reliably used the subjective judgments, understanding improved with age.

ERP Results

Grand average waveforms for encoding (Experiment 1) and retrieval (Experiment 2) are presented in Figures 4 and 5, respectively. At encoding, items subsequently given a remember judgment elicited a more positive amplitude response than familiar and missed items between 700-900 ms. This effect was not modulated by age group. In contrast, memory effects differed as a function of age group at retrieval. Retrieval memory effects were not reliable in children, widespread across the scalp in adolescents, and, consistent with previous studies (for reviews see Friedman & Johnson, 2000; Rugg & Curran, 2007), maximal over left centro-parietal leads in adults. Supporting analyses are reported below.

Subsequent recollection ERP effect at encoding not modulated by age group. Analysis of the 700-900 ms time window during encoding **(**from Experiment 1) showed a main effect of Condition, $F(2, 126) = 6.9$, $p < .01$, $\eta_p^2 = .1$. The results revealed a recollection effect, which is characterized by a more positive amplitude response to items subsequently given remember judgments than items given familiar judgments ($p = .02$) and missed items ($p < .01$), which did not differ from one another ($p = 1.0$; see Figure 4). No factors significantly interacted with Condition, *ps* > .11.

Recollection ERP effect at retrieval modulated by age group. Analysis of the 500-700 ms time window during retrieval (from Experiment 2) revealed an Age Group x Condition interaction, $F(4, 130) = 4.57$, $p < .01$, $\eta_p^2 = .12$, and an Age Group x Condition x Sagittal Plane interaction, $F(8, 260) = 2.86$, $p = .01$,$\eta_p^2 = .08$. The main effect of and additional interactions with Condition were not significant, *ps* > .19. To decompose the interactions, Condition x Sagittal x Coronal ANOVAs were conducted separately for each Age Group. No main effect of or interaction with Condition was present in children, *ps* > .11 (see Figures 5 and 6). In adolescents, there was a significant main effect of Condition, $F(2, 36) = 7.3$, $p < .01$, $\eta_p^2 = .29$.

No factors significantly interacted with Condition, *ps* > .31. The results suggested a recollection effect with remembered items showing a trend of eliciting a more positive response than familiar items ($p = .09$) and significantly eliciting a more positive response than correctly rejected items ($p < .01$). Familiar and correctly rejected items did not differ from one another ($p = 1.0$; see Figures 5 and 6). For adults, there was a main effect of Condition, $F(2, 56) = 7.1$, $p < .01$, $\eta_p^2 = .2$, that was qualified by a Condition x Coronal Plane interaction, $F(4, 112) = 4.09$, $p = .01$, $\eta_p^2 = .13$, and a Condition x Sagittal Plane interaction, $F(4, 112) = 4.44$, $p < .01$, $\eta_p^2 = .14$. This pattern of results emerged because, consistent with previous studies (see Friedman & Johnson, 2000 for review), the recollection effect in adults was maximal over left centro-parietal leads (see Figures 5 and 6). To follow-up these interactions, Condition x Coronal Plane ANOVAs were conducted at each Sagittal Plane. A recollection effect was present across left leads (i.e., F3, C3, P3), $F(2, 56) = 6.41$, $p < .01$, $\eta_p^2 = .19$. Remembered items elicited a significantly larger response than familiar ($p = .02$) and correctly rejected items ($p = .01$). For midline leads, there was a main effect of Condition, $F(2, 56) = 8.84$, $p < .01$, $\eta_p^2 = .24$, and a Condition x Coronal Plane interaction, $F(4, 112) = 5.11$, $p < .01$, $\eta_p^2 = .15$. The Condition x Coronal Plane interaction was probed by assessing the effect of Condition separately for each midline lead. A main effect of Condition was present at midline frontal, $F(2, 56) = 3.24$, $p = .05$, $\eta_p^2 = .1$, central, $F(2, 56) = 8.82$, $p < .01$, $\eta_p^2 = .24$, and parietal leads, $F(2, 56) = 11.5$, $p < .01$, $\eta_p^2 = .29$. At the midline frontal lead, the pairwise comparisons between condition means were not significant. At the central midline lead, there was a significant recollection effect; remembered items elicited a significantly larger amplitude response than familiar ($p = .01$) and correctly rejected items ($p = .01$). At the parietal midline lead, remembered ($p < .001$) and correctly rejected items ($p = .05$) elicited a larger amplitude response than familiar items. There was no difference between the amplitude elicited to remembered and correctly rejected items (p = .1). For right leads, there was a main effect of Condition, $F(2, 56) = 5.12$, $p = .01$, $\eta_p^2 = .16$, and a Condition x Coronal Plane interaction, $F(4, 112) = 3.98$, $p = .01$, $\eta_p^2 = .4$. The Condition x Coronal Plane interaction was probed by assessing the effect of Condition separately for each midline lead. No main effect of Condition was present at right frontal or central leads ($ps > .08$). A main effect of Condition was present at the right parietal lead, $F(2, 56) = 10.65$, $p < .01$, $\eta_p^2 = .28$. Similar to the effect at the midline parietal lead, remembered ($p < .01$) and correctly rejected items ($p = .01$) elicited a larger amplitude response than familiar items. There was no difference between the amplitude elicited to remembered and correctly rejected items ($p = .42$).

Discussion

The present studies examined ERP effects associated with the subjective experience of recollection utilizing Tulving's (1985) remember/know paradigm at encoding and retrieval in children, adolescents, and adults. Overall, results suggest that children can mentally re-experience the past and that age-related differences in this ability likely arise from the development of post-encoding processes (i.e., consolidation, storage, retrieval).

All age groups reliably made subjective judgments of recollection as indexed by the correspondence between accurate memory for objective contextual details (i.e., item color and semantic judgments made at encoding) and remember/know judgments about the quality of their memories. The ability of children to reliably make remember/know judgments is consistent with the results reported by Ghetti and colleagues (2011). Specifically, participants provided more falsely recognized novel items with familiar judgments and had better memory for contextual details (i.e., color and the semantic judgment made at encoding) when they gave remember judgments. Despite the fact that all age groups reliably made these judgments, older participants made them more reliably. This finding provides additional support that, contrary to previous suspicions that children would not be able to reliably introspect on the quality of their memory (Brainerd et al., 2003, 2004; Ghetti et al., 2002), children can indeed reliably make remember/know judgments. Additionally, we also found that the metacognitive ability to reflect upon the contents of one's own memories improves with age. Future research is needed to assess what effect the development of the subjective experience of recollection has on children's behavior (e.g., decision making), learning in educational settings, and competencies as eyewitnesses.

The ERP results significantly add to our understanding of the mechanisms underlying developmental differences in recollection. As hypothesized based on previous research demonstrating that ERP responses at encoding 400-1000 ms poststimulus onset in adults are related to the subsequent recollection of those stimuli (e.g., Duarte et al., 2004; Friedman & Trott, 2000; Mangels et al., 2001; Yovel & Paller, 2004), the present study found that ERP responses recorded at encoding were sensitive to recollection 700-900 ms poststimulus onset. Items given a remember judgment elicited a larger positive amplitude response than familiar and missed items. However, contrary to our hypothesis, the recollection effect at encoding did not differ among 6- to 8-year-old children, 12- to 13-year-old adolescents, and young adults. A previous developmental ERP study of the subsequent memory effect using an objective paradigm found differences in the timing, direction, and topography of an ERP effect associated with recognition between 6-year-old children and adults (Rollins & Riggins, 2013). However, consistent with other studies using this method, Rollins and Riggins (2013) did not find a recollection effect in either age group (Duarte et al., 2004; Friedman & Trott, 2000; Guo et al., 2006). The difference in findings between the present report and Rollins and Riggins (2013) could be due to the use of the remember/know paradigm (since neuroimaging studies have identified dissociations between neural regions involved in subjective and objective assessments of recollection (e.g., Duarte et al., 2008), the inclusion of children approximately one year older, or a combination of these, and possibly other, factors.

The present data suggested that age-related differences in recollection are largely due to the development of processes that occur after encoding, such as consolidation, storage, or retrieval. Consistent with our hypothesis and decades of research using subjective and objective measures of recollection (for reviews see Friedman & Johnson, 2000; Rugg & Curran, 2007), the present study found that the amplitude of the response elicited to remembered items by adults was greater than familiar and novel items and that this effect was maximal over left centro-parietal leads. Also consistent with our hypothesis, this effect was modulated by age. An effect that was similar, but more topographically widespread, effect was observed in adolescents, and a memory effect was not observed in children. Acknowledging that null findings should be interpreted with caution, many possible explanations could account for the absence of a memory effect in children. For example, it is possible that, due to developing metacognitive abilities, children made remember judgments for items when they should have made familiar judgments. If, similar to adolescents and adults, children elicit larger amplitude responses to recollected items but falsely provided familiar items with remember judgments, the amplitude of the response to remembered items would have been reduced, as was observed. Another possible explanation is that different ERP components contribute to the observed waveforms with age (see Luck, 2005, p. 53-54, for discussion over how overlapping components interact to influence the observed waveform). These components could have interacted in such a way that resulted in the null effect in children.

The present pattern of results also suggests developmental changes in the localization and specialization of neural activity associated with recollection, which could be due to the development of specific neural regions as well as their connectivity (e.g., Johnson, 2001). Localization and specialization of function with age is common in developmental cognitive neuroscience and has been previously identified in previous studies of memory during childhood (e.g., Ghetti et al., 2010; Güler & Thomas, 2013; Riggins, Geng, Blankenship, & Redcay, 2016). For example, a recent study demonstrated that at rest hippocampal functional connectivity to regions “outside” the hippocampal memory network was positively correlated with recollection in 4-year-old children but negatively corelated with recollection in 6-year-old children (Riggins et al., 2016). Similarly, hippocampal activity at encoding becomes increasingly specialized for recollection between 8- and 14 years of age (Ghetti et al., 2010), and, at retrieval, 8- to 9-year-old children are less likely to recruit regions of left ventrolateral prefrontal cortex and left inferior parietal cortex than 12- and 13-year-old children (Güler & Thomas, 2013). Thus, it is possible that the development of and connectivity between neural regions that support recollection in adults (i.e., medial temporal lobes, prefrontal cortex, parietal cortex) may have contributed to the developmental differences in ERP correlates of recollection observed in the present study. To further understanding of neural mechanisms underlying the development of the subjective experience of recollection, future fMRI research should investigate age-related differences in brain regions activated during encoding and retrieval while participants perform the remember/know paradigm.

Despite the strengths of the present research, some limitations should also be noted. One limitation of the present studies is that separate participants were included in analyses of encoding and retrieval. ERP studies in adults typically analyze data from the same participants at encoding and retrieval (e.g., Duarte et al., 2004). If we had required participants to remain motion restricted for cap application and the duration of the task (approximately 1 hour and 15 minutes) as well as contribute the minimum of 10 trials for all three conditions for both encoding and retrieval, we would have experienced significantly more data loss, especially from the youngest group of participants (6 to 8-year-olds). Even within the present studies, data loss was higher in Experiment 2, which had a recording duration of approximately 30 minutes compared to Experiment 1, which had a recording duration of approximately 15 minutes. A second limitation is that performance on the remember/know paradigm may not be a process-pure index of recollection and familiarity (Wixted & Mickes, 2010). Differences between items given remember and familiar judgments may also be partially due to differences in memory confidence. Participant reliance on confidence to make remember/know judgments across development needs to be investigated in future research.

Summary

The present study utilized the remember/know paradigm to assess ERP correlates of recollection during memory encoding and retrieval in children, adolescents, and adults. This study is an important contribution to the study of memory development because it focused on the subjective experience of recollection, which is an important component of episodic memory (Tulving, 1985). Specifically, this study fills a significant gap in the literature on memory development by examining age-related differences in neurocognitive mechanisms that underlie the subjective experience of recollection across a wide age range to improve current understanding of recollection across the lifespan. The results demonstrated that the ERP recollection effect at encoding was comparable among children, adolescents, and adults whereas the ERP recollection effect at retrieval was not present in children, topographically widespread in adolescents, and maximal over left centro-parietal leads in adults. These findings suggest that age-related improvements in the subjective experience of recollection from childhood to adulthood are primarily attributable to the development of processes that follow the initial encoding of stimuli (i.e., consolidation, storage, retrieval). Future research is needed to assess which brain regions support the development observed and what impact the development of the subjective experience of recollection has on children's behavior.

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Table 1

ERP Trial Numbers

	Children			Adolescents			Adults		
Encoding	*M*	*SD*	Range	*M*	*SD*	Range	*M*	*SD*	Range
Remember	33	15	10-62	33	14	12-58	31	13	14-59
Familiar	23	8	11-34	31	15	13-62	34	14	14-70
Missed	32	11	10-48	33	11	13-71	26	11	10-48

	Children			Adolescents			Adults		
Retrieval	*M*	*SD*	Range	*M*	*SD*	Range	*M*	*SD*	Range
Remember	24	9	11-39	32	16	15-72	34	15	13-70
Familiar	19	8	10-38	31	14	11-54	30	16	11-76
Correct rejections	38	8	27-53	45	10	29-58	46	7	30-59

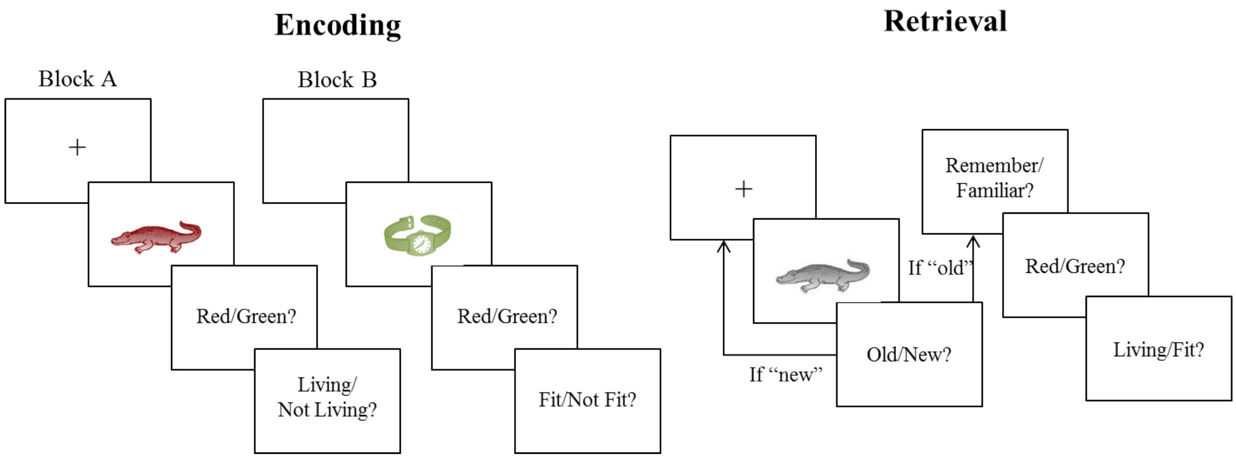

Encoding
Block A
Block B
+
Red/Green?
Living/
Not Living?
Red/Green?
Fit/Not Fit?
Retrieval
+
Remember/
Familiar?
If "old"
Red/Green?
Old/New?
If "new"
Living/Fit?

Figure 1.

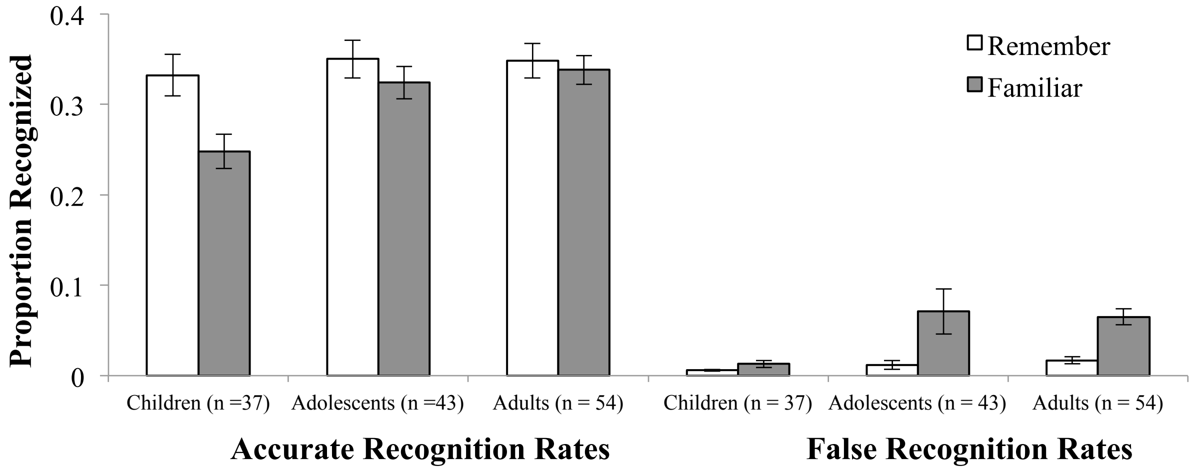
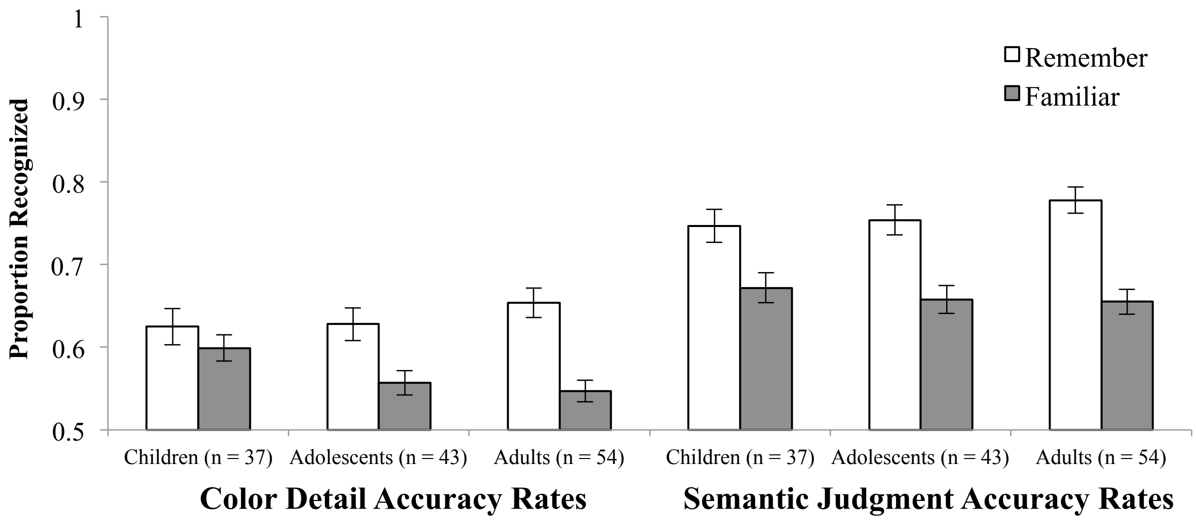

Proportion Recognized
0.4
0.3
0.2
0.1
0
Remember
Familiar
Children (n =37)
Adolescents (n =43)
Adults (n = 54)
Children (n = 37)
Adolescents (n = 43)
Adults (n = 54)
Accurate Recognition Rates
False Recognition Rates

Figure 2.



Remember
Familiar
Proportion Recognized
1
0.9
0.8
0.7
0.6
0.5
Children (n = 37)
Adolescents (n = 43)
Adults (n = 54)
Children (n = 37)
Adolescents (n = 43)
Adults (n = 54)
Color Detail Accuracy Rates
Semantic Judgment Accuracy Rates

Figure 3.

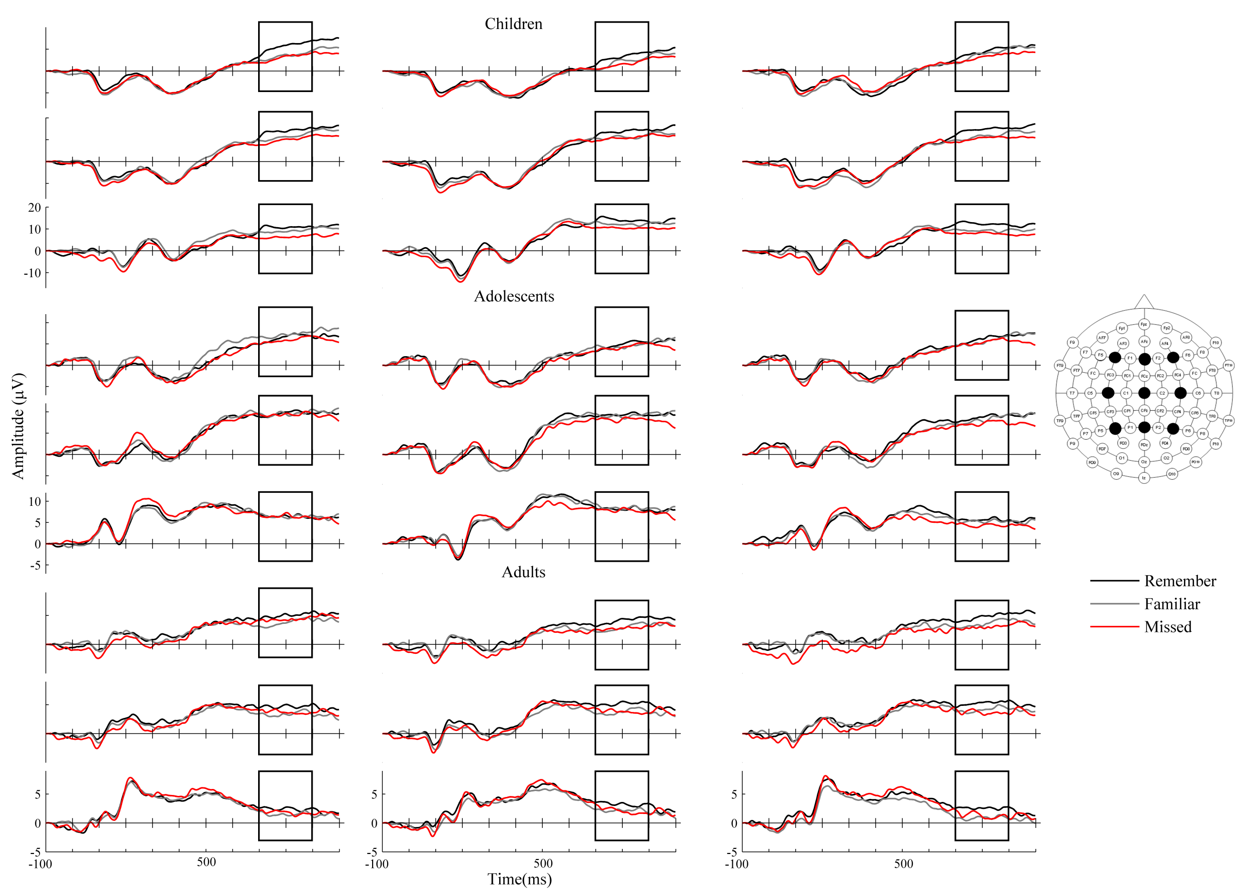

Children
Adolescents
Adults
Amplitude (µV)
Time(ms)
20
10
0
-10
5
-5
-100
500
Remember
Familiar
Missed

Figure 4.

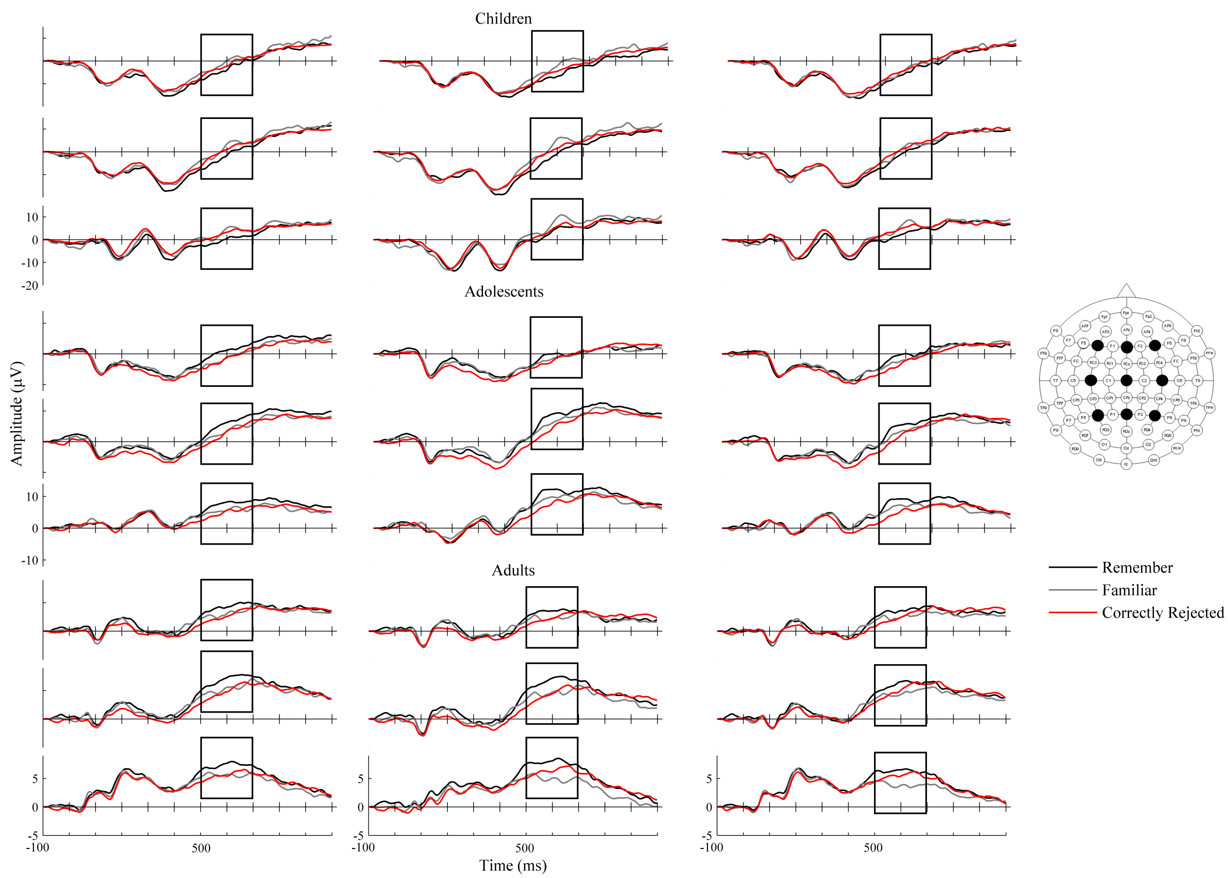

Children
Adolescents
Adults
Amplitude (µV)
Time (ms)
10
0
-10
-20
5
-5
-100
500
Remember
Familiar
Correctly Rejected

Figure 5.

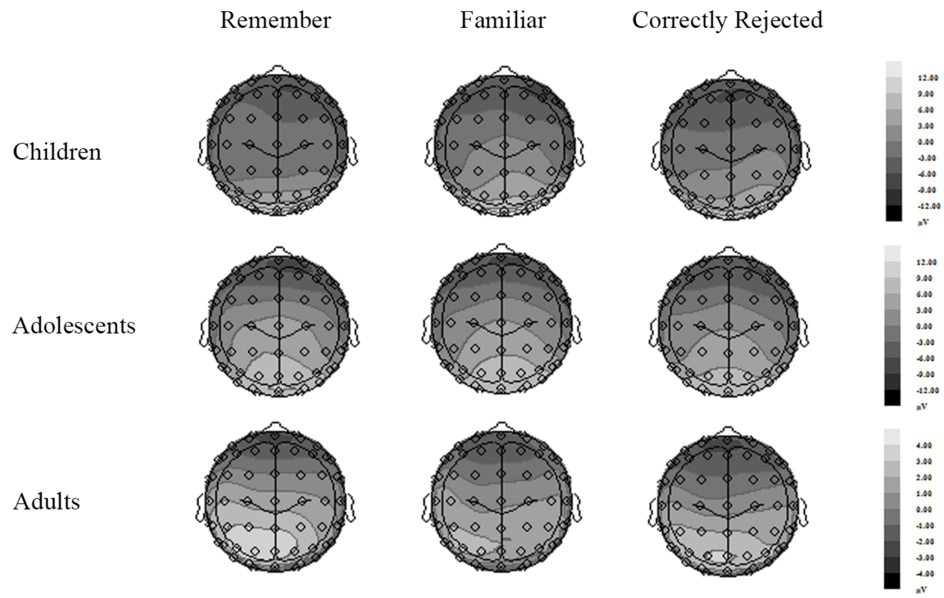

Remember
Familiar
Correctly Rejected
Children
Adolescents
Adults

Figure 6.

Figure Captions

Figure 1. Memory paradigm.

Figure 2. Mean accurate and false recognition rates for children, adolescents, and adults combined across experiments. Error bars represent standard errors.

Figure 3. Mean accuracy rates for color and semantic judgment made at encoding as a function of subjective judgment combined across experiments. An accuracy rate of .5 represents chance performance. Error bars represent standard errors.

Figure 4. Grand average waveforms recorded at encoding (Experiment 1) illustrating ERPs to items subsequently classified as remembered, familiar, and missed. Items subsequently given a remember judgment elicited a more positive amplitude response than familiar and missed items 700-900 ms poststimulus onset. This effect did not differ as a function of age group. Due to differences in overall amplitude, scaling differs across age groups.

Figure 5. Grand average waveforms recorded at retrieval (Experiment 2) illustrating ERPs to items classified as remembered, familiar, and correctly rejected. In the 500-700 ms time window, children did not demonstrate reliable memory effect, adolescents demonstrated a widespread recollection effect (as indicated by a main effect of Condition), and adults demonstrated a recollection effect maximal over left centro-parietal leads. Due to differences in overall amplitude, scaling differs across age groups.

Figure 6. Voltage maps for items classified as remembered, familiar, and correctly rejected for each age group. Data are displayed for the 500-700 ms time window. Different scales are used for children and adolescents relative to adults to account for age-related amplitude differences.