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Changes in Familiarity and Recollection across the Lifespan: An ERP Perspective

David Friedman¹, Marianne de Chastelaine², Doreen Nessler¹, and Brenda Malcolm¹

¹Cognitive Electrophysiology Laboratory, Division of Cognitive Neuroscience, New York State Psychiatric Institute, New York, New York 10032

²Center for the Neurobiology of Learning and Memory, Department of Neurobiology and Behavior, University of California, Irvine, CA 92697

Abstract

The ability to recognize previous experience depends on two neurocognitive processes, familiarity, fast-acting and relatively automatic, and recollection, slower-acting and more effortful. Familiarity appears to mature relatively early in development and is maintained with aging, whereas recollection shows protracted development and deteriorates with aging. To assess this model, ERP and behavioral data were recorded in children (9–10 years), adolescents (13–14), young (20–30) and older (65–85) adults during a recognition memory task in which the same items were studied and tested over four cycles. Participants decided whether each item was old or new and then whether the decision was associated with (Remember, R) or without (Know, K) contextual detail. Memory sensitivity was greatest in young adults, although all groups showed increases in memory sensitivity and R judgments with repetition. Familiarity-based processes (mid-frontal episodic memory, EM, effect) appeared to be used by adolescents, young and older adults, but apparently not to the same extent by children. Recollection-based processes (parietal EM effect) were recruited by children, adolescents and young adults, but to a much lesser extent by older adults. Repetition enhanced the parietal effect in all but older adults. However, post-hoc analyses indicated that reduced recollective processing was confined to poor-performing older adults. By contrast, children appeared to rely mainly on recollection concordant with their conservative decision criteria across tests. We conclude that episodic-memory development reflects the increasingly flexible and interchangeable use of familiarity and recollection with a breakdown in the latter at older ages, perhaps limited to poor-performing older adults.

Keywords

ERP episodic memory effect; lifespan; cognitive development; cognitive aging; familiarity; recollection

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Address correspondence to: David Friedman, Ph.D. Cognitive Electrophysiology Laboratory, Unit 6 New York State Psychiatric Institute, 1051 Riverside Drive, New York, New York 10032 Phone: 212-543-5476 Fax: 212-543-6002 df12@columbia.edu URL: <http://cepl.nyspi.org/>.

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INTRODUCTION

Memory for previous experience is a fundamental aspect of everyday functioning. In daily life, such memories are extremely valuable because they enable us to apply previous experience in the service of current decision making and problem solving. In the laboratory, episodic memory has been assessed typically by variants of the old/new recognition memory paradigm (Mandler, 2008). According to dual-process theorists (Mandler, 1980; Yonelinas, 2002), our ability to recognize previous episodes depends upon two neurocognitive processes: familiarity, thought to be fast-acting and relatively automatic, and recollection, slower and more effortful. The former presumably supports the capacity to simply “know” that an event was previously encountered, while the latter is thought to underlie the retrieval of contextual detail that accompanied the original episode. A great deal of behavioral as well as neuroimaging data (event-related potential, ERP, and functional magnetic resonance imaging, fMRI), at least in young-adult samples, supports a functional, temporal and neural distinction between these two sets of processes, thus supporting dual-process models of episodic memory (Eichenbaum, Yonelinas, & Ranganath, 2007; Friedman & Johnson, 2000; Rugg & Yonelinas, 2003; Rugg & Curran, 2007; Yonelinas, 2002; but see Paller, Voss, & Boehm, 2007, and Squire, Wixted, & Clark, 2007).

Despite the importance of episodic memory in the development of cognition throughout childhood and adolescence (Ornstein & Haden, 2001), developmental and lifespan investigations of mnemonic function are relatively scarce. Nonetheless, performance indices from these tasks generally indicate that episodic memory develops throughout childhood, reaches adult-like levels by adolescence and declines with aging (Billingsley, Smith, & McAndrews, 2002; Cycowicz, Friedman, Snodgrass, & Duff, 2001; Cycowicz, Friedman, & Duff, 2003; de Chastelaine, Friedman, & Cycowicz, 2007; Park, et al., 2002). Less clear, at least from a developmental perspective, are the relative contributions that familiarity- and recollection-based processes make to these overall trends. Here, we sought to redress this situation and obtain a more precise estimate of the lifespan trajectory of processes thought to underlie episodic memory via the inclusion of children (9-10 years old), adolescents (13-14), young (20-30) and older (65-85) adults.

The results of age-related behavioral investigations suggest that familiarity-based processing is maintained across the lifespan, whereas recollection declines (Hay & Jacoby, 1999; Howard, Bessette-Symons, Zhang, & Hoyer, 2006; Jennings & Jacoby, 1997; Prull, Dawes, Martin, Rosenberg, & Light, 2006; but see Duarte, Graham, & Henson, 2008). However, developmental studies are extremely rare. Billingsley, et al. (2002) studied groups of 8-10, 11-13, 14-16, and 17-19 year olds with study-test recognition and cued-recall paradigms. For both tasks, subjects had to indicate if their retrieval of old items was accompanied by recollection of contextual details (Remember or R judgment) or not (Know or K judgment; Tulving, 1985). As might be expected, there were no age differences in the percentage of judgments based on familiarity, while the percentage of old items retrieved via recollection showed a reliably increasing developmental course. Similarly, Ofen, et al. (2007) reported that, whereas recognition memory associated with R judgments improved between the ages of 8 and 24, familiarity-based recognition was maintained at similar levels within this age range. These general developmental trends (between 6- and 18-years of age) were corroborated, using receiver operating characteristics (ROC; Yonelinas, 2002) by Gheiti & Angelini (2008). Hence, at this stage of knowledge, the limited data suggest that familiarity is in place relatively early in the developmental sequence (even infants are thought to exhibit familiarity-based recognition - Nelson, 1995; Slater, Morison, & Rose, 1984) and is maintained with aging, whereas recollection-based processes show a relatively prolonged maturational course and decline in aging.

However, the behavioral response on which memory performance is typically based (reaction time; RT), is the “final common pathway” for a number of stages that intervene between the presentation of the copy cue and the old/new judgment. The temporal precision of the ERP technique is advantageous here because, as described below, two, sequentially-occurring components have been associated with familiarity- and recollection-based processes. Hence, ERPs provide an ideal method for investigating dual-process models from developmental and age-related perspectives (for reviews, see Friedman & Johnson, 2000; Rugg & Yonelinas, 2003; Wilding & Sharpe, 2002).

The ERP effects thought to reflect familiarity- and recollection-based processes take the form of differences between the waveforms associated with correctly-recognized old (hereafter, Hits) and correctly-rejected new (hereafter CRs) items. These have been referred to as episodic memory (EM) effects by Friedman and Johnson (2000), and this terminology will be used here. Although currently controversial (Paller, et al., 2007; Rugg & Curran, 2007), a variety of evidence suggests that familiarity-based processing is associated with an enhanced positivity for Hits relative to CRs, maximal over mid-frontal scalp sites between approximately 300-500 ms post-stimulus. This modulation has been referred to as the mid-frontal EM effect. A general consensus suggests that recollection-based processes are indexed by a later-onsetting, enhanced positivity, also larger to Hits than CRs, maximal over parietal scalp locations between 500-700 ms post-stimulus. This has been labeled the parietal EM effect.

The association of the mid-frontal EM effect with familiarity is based upon observations that its amplitude is similar to 1) hits regardless of whether they are endorsed with remember or know judgments (Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999), 2) hits regardless of whether the contextual details from the original episode are correctly identified (Friedman, 2004), and 3) hits and falsely recognized items that are highly similar to previously studied old items, i.e., “lures” (Curran, 2000; Nessler, Mecklinger, & Penney, 2001). The subsequent parietal EM effect has been associated with recollection because its amplitude 1) is larger to hits associated with R compared to K judgments (Smith, 1993; Trott, et al., 1999), 2) is larger to hits associated with correct compared to incorrect source judgments (Wilding & Rugg, 1996), 3) is larger to hits compared to falsely recognized, highly similar lure items (Curran, 2000), and 4) is larger the greater the amount of information retrieved (Vilberg & Rugg, 2009; Wilding, 2000). Consistent with the mid-frontal and parietal EM effects reflecting distinct mnemonic processes, the evidence indicates that they are associated with reliably different scalp distributions, compatible with the notion that these effects are associated with different neural substrates (Friedman, 2004; Johnson, Kreiter, Russo, & Zhu, 1998; Rugg & Yonelinas, 2003).

Unfortunately, data concerning developmental changes in the electrophysiological signs of familiarity and recollection are scant (see Ofen, et al., 2007, for an fMRI study). In one such ERP study, Czernochowski, Mecklinger, Johansson, and Brinkmann (2005) investigated the familiarity - recollection distinction in 6-8 and 10-12 year old children and young adults (20-29 years of age) using a recognition-memory exclusion task (Jacoby, 1991). Both item- (i.e., content or familiarity-based) and source- (i.e., contextual or recollection-based) memory accuracy increased with age. In addition, source-, relative to item-, memory performance was poorer in all three age groups although, as might be expected, this latter difference was much more marked in the children. Although the behavioral studies reviewed above suggest that children do recruit familiarity-based processes, Czernochowski, et al. (2005) did not observe putative mid-frontal familiarity effects in the children's waveforms, although these were present in the young-adult ERPs. Nonetheless, despite children's overall poorer performance, all groups showed evidence of presumed recollection-based processes (parietal EM effects). These findings led Czernochowski and coworkers (2005; see also Czernochowski, Mecklinger, & Johansson, 2009) to conclude that children relied primarily on recollection to make their

recognition-memory decisions, whereas young adults employed familiarity and recollection flexibly. As noted, this interpretation runs counter to the behavioral studies reviewed earlier, the majority of which conclude that familiarity-based processes are functional within this age range. Thus, because the Czernochowski, et al. (2005) data are some of the only ERP developmental data available at this time, they require replication to come to a more definitive conclusion.

Compared to the paucity of developmental studies, the neural underpinnings of familiarity and recollection have been assessed a bit more often in cognitive aging studies. Though the findings come from a small number of investigations, with some exceptions (Duarte, Ranganath, Trujillo, & Knight, 2006; Duarte, et al., 2008), they fit most theoretical accounts of the cognitive aging of memory by suggesting that, as noted earlier, relative to recollection-based processing which declines, familiarity-based processing is generally maintained with aging (Prull, et al., 2006; Howard, et al., 2006; Yonelinas, 2002). For example, Nessler, Friedman, Johnson, and Bersick (2007; see also Trott, et al., 1999) asked young and older adults to study the same nouns during two encoding blocks, each of which was followed by an old/new recognition test. Recognition performance was greater for young compared to older adults and for both groups following repetition. However, older, relative to young adults appeared to benefit more from repetition, an effect that was associated with an age-related change in the observed ERP pattern. Specifically, while young and older adults showed mid-frontal EM effects of equal magnitude in Tests 1 and 2, suggesting age invariance in the recruitment of familiarity-based processes, a different pattern was observed for the putative neural correlate of recollection. Only young adults showed a reliable parietal EM effect in Test 1 and, in line with behavioral performance, an enhanced parietal EM effect in Test 2. Repetition appeared to enable recollection in older adults as well, as they showed a reliable parietal effect in Test 2, which however, was significantly smaller than that found for young adults. Hence, although repetition appeared to enable older adults to engage, at least some, recollection-driven retrieval processing, this processing was diminished with aging while familiarity-based recognition was maintained.

The current study's overall goal was to build on these very limited findings by recording ERP and performance measures in a study-test paradigm, in which the same set of objects was studied and tested four times (Johnson, Pfefferbaum, & Kopell, 1985). A previous paper has described the young adult data resulting from this paradigm (de Chastelaine, Friedman, Cycowicz, & Horton, 2009). Here we add child, adolescent and older adult groups, thereby enabling a lifespan perspective on the contribution of familiarity- and recollection-based processes to developmental and age-related changes in episodic memory function.

The young-adult data described by de Chastelaine, et al. (2009) revealed important insights into the interplay between familiarity- and recollection-based processes. These investigators employed symbol-like objects that were pre-experimentally unfamiliar and, at least initially, unnamable. This was done to overcome the difficulty associated with the use of highly pre-experimentally familiar verbal or pictorial concepts. Use of these latter types of stimulus materials has led to considerable debate concerning whether the mid-frontal EM effect reflects conceptual fluency or familiarity (Paller, et al., 2007; Rugg & Curran, 2007; Stenberg, Hellman, Johansson, & Rose, 2008). In the de Chastelaine, et al. (2009) investigation, repetition across four study-test blocks did not modulate presumed familiarity-based processing over mid-frontal locations. However, repetition had two effects: 1) recollection-based processing over parietal scalp sites was enhanced across test blocks (see also Nessler, et al., 2007); and 2) the onset of these processes occurred earlier with repetition. Specifically, the onset latency of the parietal EM effect (500-700 ms) shifted into the earlier 300-500 ms window. In addition, the scalp distribution of the 300-500 ms interval, which showed a mid-frontal focus in the early test blocks, changed to a parietal topography in the last test block (labeled the "early parietal old/new effect" by de Chastelaine, et al., 2009). Thus, as more information about the symbol-

like events presumably accrued over test blocks, putative recollection-based processes occurred earlier in time and appeared to predominate over familiarity-based processes.

Based on the limited lifespan performance and ERP data, as well as the results of de Chastelaine, et al. (2009), specific predictions were considered. All age groups were expected to show increments in memory sensitivity across test blocks and an associated increment in the percentage of R judgments, although this effect might be more pronounced in young adults, especially in comparison with older adults. For the adult groups at least, familiarity was expected to be manifested by the presence of reliable mid-frontal EM effects. As more contextual information about studied items accrued via repetition, based on the data of de Chastelaine, et al. (2009), the parietal EM effect was expected to increase and occur with earlier onset for young adults. Because, relative to younger children, adolescents have shown increments in recollection-based processing (Billingsley, et al., 2002)), it was reasonable to expect that they might also demonstrate a decrease in the onset latency of the recollection-related parietal EM effect. Based on the finding that children appear able to recruit recollection-based processes during recognition testing (Berman, Friedman, & Cramer, 1990; Cycowicz, et al., 2003; Czernochowski, et al., 2005), we predicted that children would also show increments in ERP recollection-based processing effects and perhaps earlier onset of these processes across test phases. As older adults appear to have a selective deficit in recollection, this effect was expected to be reduced in this group. Children have also produced behavioral estimates of familiarity-based processing of equivalent magnitude to young adults. On this basis, we expected that this group might show ERP evidence of familiarity-driven processes (mid-frontal EM effect), although two studies by Czernochowski and colleagues have failed to observe this effect in children (Czernochowski, et al., 2005; Czernochowski, Mecklinger, & Johansson, 2009).

RESULTS

Behavioral Data

Table 1 presents the mean reaction time (RT), percentage correct, memory sensitivity (Pr) and response bias (Br) measures (Snodgrass & Corwin, 1988) in Tests 1&2 and 3&4 for the four age groups.

Accuracy—Importantly, as assessed by one-sample t-tests, all groups showed Pr values (Hits-False Alarms) that were reliably different from 0. To assess whether repetition impacted differentially the memory sensitivity of the 4 age groups (Table 1), Pr was subjected to an ANOVA with one between-Age Group factor and one within-subjects factor, Test Phase (Tests 1&2, Tests 3&4). The reliable Age Group main effect ($F(3,62) = 12.11, P < 0.0001, \eta^2 = .37$) indicated, as assessed by post-hoc tests, that young adults showed overall greater memory sensitivity than all other groups who did not differ significantly. The significant Test Phase main effect ($F(1,62) = 256.31, P < 0.0001, \eta^2 = .86$) reflected a reliable increase in Pr across test blocks in similar fashion for all four age groups (Test Phase $\times$ Age Group interaction $F < 1$).

Similar to Pr, the Br values of all age groups were significantly different from 0. To determine if response bias changed in a systematic manner across test blocks in different fashion for the four age groups, the same Test Phase $\times$ Age Group ANOVA was performed on the Br values. The main effects of Age Group ($F(3,62) = 7.40, P < 0.0001, \eta^2 = .26$) and Test Phase were significant ($F(1,62) = 26.20, P < 0.0001, \eta^2 = .29$). As shown in Table 1, children tended to produce the most conservative response bias measures. Consequently, post-hoc testing revealed that children generated more conservative Br values than young and older adults. The adolescents did not differ reliably from the children or young adults, but did show more conservative decision criteria than older adults. Young and older adults did not differ

significantly. However, Age Group and Test Phase interacted ($F(3,62) = 11.57, P < 0.0001, \eta^2 = .36$). Subsidiary ANOVAs performed separately for each group revealed that young adults showed a conservative bias in Tests 1&2 which became reliably more liberal (i.e., > 0.5 ; Snodgrass & Corwin, 1988) in Tests 3&4 ($F(1,17) = 40.26, P < 0.0001, \eta^2 = .70$). Similarly, adolescents' decision criteria became reliably less conservative across test phases ($F(1,14) = 4.50, P < 0.05, \eta^2 = .24$; see Table 1). The differences between Tests 1&2 and 3&4 were not reliable for either children ($F < 1$), who showed conservative biases across test phases, or older adults ($F(1,16) = 2.73, P > 0.10$), who tended towards neutral biases during both sets of test blocks.

R and K Judgments—Lifespan changes in familiarity- and recollection-based processing were assessed using adjusted measures of R and K performance (de Chastelaine, et al., 2009). Table 2 depicts the proportions of R and K judgments for the two test phases and each age group. The proportion of old items associated with R responses was adjusted to take into account the proportions of false alarms. Thus, differences between the proportions of old and new items associated with R judgments were calculated as follows: **adjusted pRold = pRold - pRnew**; **adjusted pKold = pKold - pKnew**. Under the assumption that R and K judgments depend on independent processes (Yonelinas & Jacoby, 1995), an estimate of familiarity was computed by dividing the proportion of old items attracting K judgments by 1 minus the proportion of old items given R judgments, and adjusted by performing the same calculations on the proportions of false alarms (i.e., $[\text{pKold}/(1 - \text{pRold})] - [\text{pKnew}/(1 - \text{pRnew})]$). **These adjusted values appear in Table 3.** All of these adjusted measures differed reliably from 0, as assessed by one-sample t-tests. The corrected R and K indices were then subjected separately to Age Group $\times$ Test Phase ANOVAs.

Recollection-based processing (on the adjusted R measures – Table 3) increased from Tests 1&2 ($M = 0.23$) to Tests 3&4 ($M = 0.43$; $F(1,62) = 137.42, P < 0.0001, \eta^2 = .69$). The Age Group main effect was also significant ($F(3,62) = 4.11, P < 0.01, \eta^2 = .16$). As assessed by post-hoc testing, young adults ($M = .46$) produced greater recollection rates than children ($M = 0.25$) and older adults ($M = .27$), but not adolescents ($M = 0.33$); these latter three groups did not differ significantly. However, Age Group interacted with Test Phase ($F(3,62) = 2.85, P < 0.05, \eta^2 = .12$). Subsidiary ANOVAs performed separately for each group indicated that, although repetition led to an increase in recollection in each age group ($F_s > 21.09, P_s < 0.0001$), the magnitude of the increase was greater (as revealed by post-hoc tests) for young adults ($M = 0.29$) than children ($M = 0.19$), adolescents ($M = 0.18$) and older adults ($M = 0.16$). The latter three group means did not differ reliably.

Familiarity-based responding (on the adjusted K measures – Table 3) also increased with repetition (M Tests 1&2 = 0.25; M Tests 3&4 = 0.46; $F(1,62) = 77.32, P < 0.0001, \eta^2 = .69$). The Age Group main effect ($F(3,62) = 7.96, P < 0.0001, \eta^2 = .28$) indicated, via post-hoc assessment, that young adults ($M = 0.54$) showed greater familiarity-based processing than children ($M = .24$), adolescents ($M = .31$) and older adults ($M = .35$); the latter three means did not differ reliably. However, unlike the estimate of recollection, the Age Group $\times$ Test Phase interaction was not significant ($F = 1.24$), suggesting that the increment in familiarity with repetition was similar in all 4 groups.

It is possible that, relative to young adults, the lower memory sensitivity and recollective performance in children, adolescents and older adults could have been due to a lower level of conceptual processing. As in de Chastelaine, et al. (2009), we determined the degree of “conceptual” processing from the post-experiment symbol-naming task (see Methods). The number of symbol-like objects that had been “named” or associated with a familiar object at any time during the experimental session was tallied for each participant (16 children, 15 adolescents, 17 young and 16 older adults contributed data to this analysis). These numbers

were subjected to a between Age Group ANOVA, which returned a reliable main effect of Age Group ($F(3,63) = 3.06, P < 0.05$). Post-hoc tests indicated that, although older adults ($M = 15.4$) generated a reliably lower number of naming responses relative to young adults ($M = 23.0$), their mean number did not differ significantly from that of the children ($M = 15.6$) or adolescents ($M = 18.0$). No other differences were reliable.

To further explore the possibility of differential age-related conceptual processing, the percentage of named or unnamed hits was subjected to an Age Group $\times$ Test Phase (Tests 1&2, Tests 3&4) $\times$ Naming (named, unnamed) ANOVA (1 young and 1 older adult's data were not available for this analysis). If conceptual processing had a differential age-related effect on memory performance, then we would expect an Age Group by Naming interaction. However, the ANOVA returned only reliable main effects of Naming ($F(1,60) = 37.48, P < 0.0001, \eta^2 = .38$; a greater percentage of hits was associated with named compared to unnamed objects), Test Phase ($F(1,60) = 229.42, P < 0.0001; \eta^2 = .79$; Tests 3&4 produced a greater percentage of hits than Tests 1&2) and Age Group ($F(3,60) = 6.93, P < 0.0001, \eta^2 = .25$; young adults produced a greater percentage of hits, as expected from the main analyses presented above). Importantly, there were no interactions with Age Group ($F_s < 1.4$). Hence, these data argue strongly that there was not a differential age-related effect of conceptual processing on the age-related memory performance differences observed here.

Reaction Time—To determine if repetition influenced speed of processing differentially for the four age groups, RTs to Hits and CRs (Table 1) were subjected to a between Age Group $\times$ Test Phase $\times$ Item Type (Hit, CR) ANOVA. The main effect of Age Group was significant ($F(3,62) = 21.10, P < 0.0001, \eta^2 = .51$). Post-hoc testing indicated that, collapsed across Hits and CRs, older adults responded more slowly than young adults, children and adolescents, who did not differ reliably. The main effect of Test Phase ($F(1,62) = 26.10, P < 0.0001, \eta^2 = .30$) revealed that RTs were faster in Tests 3&4 than in Tests 1&2 in similar fashion for the four groups (Repetition $\times$ Age Group $F(3,62) = 2.56, P > 0.05$). Neither the main effect of Item Type ($F < 1$) nor the Item Type $\times$ Test Phase $\times$ Age Group ($F < 1$) interaction was significant.

To summarize the behavioral data, repetition increased memory sensitivity similarly in all age groups. However, whereas young adults showed a reliable tendency to become more liberal in calling a studied item “old” as memory strength increased (a similar trend was shown by adolescents), the children's conservative and older adults' neutral biases were maintained over test phases. Importantly, repetition increased the measure of recollection in all age groups, presumably reflecting increments in access to contextual information, but the enhancement was greater in young adults than the other 3 groups. Based on the independence assumption (Yonelinas & Jacoby, 1995), familiarity-based processing was greatest in young adults and also increased over test phases for all 4 groups. By contrast with the index of recollection, the increment was similar in all 4 groups. Finally, assuming that conceptual processing could be estimated by the number of symbol-like objects that was associated with a semantic label, reduced conceptual processing was not likely to have contributed to the lower memory performance, relative to young adults, of children, adolescents and older adults.

ERP Data¹

Figure 1 depicts the grand-averaged waveforms for Hits and CRs at left (F3), midline (Fz) and right (F4) frontal, and left (P3), midline (Pz) and right (P4) parietal scalp locations recorded

¹The mean number and range of trials entering each of the 4 averages (respectively, Hits Tests 1&2, CRs Tests 1&2, Hits Tests 3&4, CRs Tests 3&4) were for children: (31, 14-46; 43, 25-58; 44, 15-73; 46, 22-57); for adolescents: (36, 16-54; 37, 16-52; 48, 21-71; 42, 21-53); for young adults: (51, 34-69; 50, 29-59; 73, 64-80; 53, 44-59); for older adults: (40, 11-62; 35, 16-49; 52, 25-75; 43, 25-56). There was an insufficient number of trials to permit the formation of ERP averages associated with R and K judgments as a function of Test Phase in children, adolescents and older adults (for these data in young adults, see de Chastelaine, et al., 2009).

during Tests 1&2 and Tests 3&4 for the children and adolescents (Figure 1A) and young and older adults (Figure 1B). These locations were used because, as described below, the EM effects of interest were all of greatest magnitude at one or more of these scalp loci. Figure 2 illustrates the scalp topographies of the 300-500 ms and 500-700 ms ERP regions for each age group and Test Phase.

Four effects are of note in Figures 1 and 2. First, in Tests 1&2, the 300-500 ms mid-frontal EM effect is distributed about the midline (maximal at Fz) in adolescents and young adults (Friedman & Johnson, 2000; Rugg & Curran, 2007), whereas in older adults it is right-lateralized, in agreement with Nessler, et al. (2007). Consistent with the data of Czernochowski, et al. (2005), the mid-frontal effect appears to be absent or dramatically reduced for children. Second, with the exception of older adults who continue to show an EM effect maximal over frontal sites in Tests 3&4, the adolescents' and young adults' data demonstrate a change from a fronto-central focus in Tests 1&2 to a parietal focus in the 300-500 ms region during Tests 3&4 (Figure 2). This parietal effect appears to onset earlier in Tests 3&4 compared to Tests 1&2 (early-onset parietal effect in Figure 1A and B and Figure 2), at least in adolescents and young adults (de Chastelaine, et al., 2009). Third, for children, adolescents and young adults, a large-magnitude, 500-700 ms, parietal EM effect is present and appears larger in Tests 3&4 compared to Tests 1&2 (over left, P3, compared to right, P4, locations and at the Pz scalp site). Fourth, although older adults evince a parietal EM effect which appears to increase slightly in magnitude over test phases, it is markedly diminished relative to that of the other groups. This reduction could be due to overlap with negative-going activity apparent only for older adults over left-frontal locations (F3), i.e., hits elicit more negative-going activity than CRs (see maps in columns 2 and 4 in the fourth row of Figure 2; see also Duarte, et al., 2006; Li, Morcom, & Rugg, 2004, and Swick, Senkfor, & Van Petten, 2006).

Averaged Voltage Analyses: Based on our predictions and the effects described above, these analyses focused on determining whether: 1) each of the four groups showed evidence of and/or differences in familiarity- (mid-frontal EM effect) and recollection- (parietal EM effect) based processing; 2) recollection- relative to familiarity-based processing increased as a function of Test Phase; and 3) recollection-based processing occurred earlier in Tests 3&4 than Tests 1&2 (early-onset parietal effect; de Chastelaine, et al., 2009) and, if so, were there age differences in this effect.

We followed the analytic strategy of de Chastelaine, et al. (2009) and first determined whether there were statistically reliable old-new effects (i.e., Hit-CR) for each interval (300-500 ms; 500-700 ms), age group and test phase at individual electrode sites where the effects were largest. Then, to determine if these EM effects increased over test phases differentially for the four age groups, the old-new difference scores were subjected to Age Group $\times$ Test Phase $\times$ Electrode Location mixed-design ANOVAs (F3, Fz, F4 for the 300-500 ms window; P3, Pz, P4 for the 500-700 ms interval). Interactions with Electrode Location are not reported unless they occurred with both Age Group and Test Phase as, by themselves, they are not relevant to the hypotheses under consideration. In the presence of Test Phase $\times$ Age Group interactions, subsidiary Test Phase $\times$ Electrode Location ANOVAs were performed separately for each age group. Tables 4 and 5 present the grand mean Hit-CR differences for, respectively, the 300-500 and 500-700 ms intervals and the results of significance testing to determine if they differed reliably from zero.

Mid-frontal EM effect (300-500 ms)—Table 4 shows that, by contrast with the three other groups, the children did not produce a reliable mid-frontal EM effect in either test phase. To assess developmental and age-related differences in presumed familiarity-based processes, the 300-500 ms old-new difference means were subjected to an Age Group $\times$ Test Phase $\times$

Electrode Location (F3, Fz, F4) ANOVA. This analysis failed to reveal a main effect of Test Phase ($F = 1.48$), indicating that the mid-frontal effect maintained similar amplitude for the two test phases. The Test Phase $\times$ Age Group ($F=1.50$) and Test Phase $\times$ Age Group $\times$ Electrode Location ($F=1.45$) interactions were not significant.

Early-onset parietal effect (300-500 ms)—Table 4 demonstrates that older adults did not show a reliable effect at either test phase, whereas adolescents and young adults did. Similar to older adults at Tests 1&2, children also did not produce a significant effect at Tests 1&2. However, by contrast with older adults, they did demonstrate a robust difference at Tests 3&4. To assess developmental and/or age-related changes in the magnitude of the early-onset parietal effect, the mean Hit-CR difference scores were submitted to an Age Group $\times$ Test Phase $\times$ Electrode Location (P3, Pz, P4) ANOVA. The main effect of Test Phase ($F(1,62) = 19.78$, $P < 0.0001$, $\eta^2 = .24$) indicated that the magnitude of the early parietal effect increased with repetition. Importantly, the Test Phase $\times$ Age Group ($F(3,62) = 4.48$, $P < 0.007$, $\eta^2 = .18$) and Test Phase $\times$ Age Group $\times$ Electrode Location ($F(6,124) = 2.63$, $P < 0.02$, $\epsilon = 0.97$, $\eta^2 = .11$) interactions were significant.

To decompose the interactions, separate Test Phase $\times$ Electrode Location ANOVAs were performed for each Age Group. For young adults ($F(1,17) = 9.41$, $P < 0.007$, $\eta^2 = .36$), adolescents ($F(1,14) = 6.74$, $P < 0.02$, $\eta^2 = .32$), and children ($F(1,15) = 8.25$, $P < 0.01$, partial $\eta^2 = .36$), the main effect of Test Phase was reliable. By contrast with these groups, older adults did not show an increase in magnitude over test phases ($F < 1$). For children, the interaction of Test Phase with Electrode Location ($F(2,30) = 4.03$, $P < 0.03$, $\epsilon = 0.96$, $\eta^2 = .21$) indicated, as assessed by post-hoc tests, that the difference between test phases was largest at Pz.

Parietal EM effect (500-700 ms)—Table 5 demonstrates that, by contrast with the early-onset parietal effect, all age groups showed reliable parietal EM effects for each Test Phase and scalp site. Developmental and age-related changes were assessed in an Age Group $\times$ Test Phase $\times$ Electrode Location (P3, Pz, P4) ANOVA. The main effect of Test Phase indicated that the parietal EM effect increased in magnitude over test phases ($F(1,62) = 14.71$, $P < 0.0001$, $\eta^2 = .19$). However, Age Group interacted with Test Phase ($F(3,62) = 5.27$, $P < 0.003$, $\eta^2 = .20$), as well as Test Phase and Electrode Location ($F(6,124) = 3.34$, $P < 0.004$, $\epsilon = 0.95$, $\eta^2 = .14$).

To find the source of these interactions, subsidiary Test Phase $\times$ Electrode Location ANOVAs were performed separately for each group. Unlike the early-onset parietal effect, the main effect of Test Phase was not reliable for adolescents ($F(1,14) = 3.17$, $P > 0.10$, partial $\eta^2 = .18$), young ($F=1.50$) or older adults ($F < 1$). However, for children, the amplitude of the parietal EM effect did increase over test phases ($F(1,15) = 9.15$, $P < 0.009$, $\eta^2 = .37$). The interaction of Test Phase and Electrode Location in the children ($F(2,30) = 4.72$, $P < 0.02$, $\epsilon = 0.85$, $\eta^2 = .24$) indicated, as confirmed by post-hoc tests, that the difference between test phases was greatest at Pz.

Onset-Latency Analyses—de Chastelaine, et al. (2009) provided evidence consistent with recollective processing occurring earlier as a function of repetition. To determine if the parietal effect occurred earlier in time with repetition in the current data and whether this effect differed among the age groups, the procedure described by de Chastelaine, et al. (2009) was followed. The old-new difference waveforms from the two Test Phases were segmented into 20 ms bins between 0-700 ms post-stimulus for each age group. T-tests were conducted in order to determine whether the averaged voltage within each bin was greater than zero. Onset latency was then defined as the time point at the beginning of the first of six consecutive time bins for which the amplitude was significantly greater than zero. These analyses were conducted on the data recorded at the P3 scalp site (data from the Pz site revealed the identical pattern of

findings). The results indicated that, from Tests 1&2 to Tests 3&4 parietal EM effects occurred at earlier latencies (**Children** Tests 1&2: 540-560 ms; Tests 3&4: 380-400 ms; **Adolescents** Tests 1&2: 420-440; Tests 3&4: 360-380 ms; **Young Adults** Tests 1&2: 360-380 ms; Tests 3&4: 280-300 ms; **Older Adults** Tests 1&2: 500-520 ms; Tests 3&4: 420-440 ms).

Left-Frontal Negativity in older Adults (500-900 ms)—To assess the reliability of the Hit vs. CR negative-going activity evident in the older adult ERPs only (at F3; Figures 1B and 2) and whether it differed reliably from that of the other groups, an Age Group $\times$ Test Phase $\times$ Item Type ANOVA was performed on the averaged voltages (500-900 ms) computed at F3. This analysis returned reliable main effects of Test Phase ($F(1,62) = 8.07$, $P < 0.006$, $\eta^2 = .11$), and Item Type ($F(1,62) = 55.78$, $P < 0.0001$, $\eta^2 = .47$) indicating, respectively, greater amplitude in Tests 3&4 than Tests 1&2, and to Hits than CRs. Importantly, Item Type and Age Group interacted ($F(3,62) = 14.54$, $P < 0.0001$, $\eta^2 = .41$). Subsidiary Test Phase $\times$ Item Type ANOVAs performed separately for each age group indicated that, whereas Hits elicited significantly more *positive-going* activity than CRs in children, adolescents and young adults ($F_s > 16.93$, $P_s < 0.0001$), in older adults, they were associated with more *negative-going* activity ($F(1,16) = 4.77$, $P < 0.04$, $\eta^2 = .23$; see Figures 1B and 2).

In summary, adolescents, young and older adults, but not children, showed evidence of putative familiarity-based processing between 300 and 500 ms (mid-frontal EM effect), which did not increase in magnitude across test phases. By contrast, presumed recollection-based processing (early-onset parietal effect) appeared to occur earlier in time and increase with repetition in children, adolescents and young adults. Then again, older adults did not evince significant, early-onset recollective processing, but did show small, though reliable 500-700 parietal EM effects. The latter may have been attenuated by the prominent left-frontal negativity exhibited in this group (Figure 1B and 2; see also Li, et al., 2004). Hence, older adults did show some, albeit reduced, evidence of recollection-based processes, but these were delayed relative to those of the other age groups.

DISCUSSION

The overall goal of the current study was to determine the relative contributions of familiarity- and recollection-based processes to the development of and age-related change in episodic memory function. Four groups of participants, 9-10 year-old children, 13-14 year-old adolescents, 20-30 year-old young and 65-85 year-old older adults were assessed with a repeated study-test recognition memory paradigm. The inclusion of this wide age range is unique in ERP studies of memory development and aging. Hence, these data, as described below, provide valuable insight into the lifespan trajectory of episodic memory function.

Behavioral Data

The ability to use recollection-based processes to make recognition memory judgments appeared similar in children, adolescents and older adults, but was greatest in young adults. Furthermore, repetition increased these estimates to a greater extent in young adults relative to the other 3 groups. Estimates of familiarity-based processing were also greatest in young adults. However, by contrast with recollection, repetition enhanced the estimate of familiarity to a similar extent in all age groups. The differential effects of repetition on the behavioral measures of recollection and familiarity add to the evidence favoring dual-process theories of recognition memory and suggest that the two processes may undergo different rates of developmental change (Ghetti & Angelini, 2008).

In accord with this conclusion, several previous studies support the idea that recollection and familiarity follow different developmental trajectories. In the current study, estimates of recollection were greatest in young adults (although the difference between adolescents and

young adults was not significant), concordant with the results of two previous developmental studies in which the R/K paradigm has been used (Billingsley, et al., 2002; Ofen, et al., 2007). These authors demonstrated that recollection-based retrievals increased from childhood through young adulthood, whereas age equivalence was observed for estimates of familiarity. The data from these two investigations suggest that familiarity is in place in children as young as 6 years of age. Similarly, using the process-dissociation procedure (Jacoby, 1991), Anooshian, 1999 (see also Zelazo, Craik, & Booth, 2004) observed no differences between pre-school children and young adults in estimates of familiarity-based processing, but reported an age-related increment in estimates of recollection. In addition, in an alternative analysis of the behavioral data described in Cycowicz, et al. (2003), Cycowicz and Friedman (unpublished observations) computed process-dissociation estimates and found that recollection increased reliably from childhood (9-10 years old) through adolescence (13-14 years old) into young adulthood (20-30 years old), while familiarity was age invariant. Ghetti and Angelini (2008) used the ROC technique with children and adolescents between the ages of 6 and 18. In their experiment 1, these authors reported that familiarity-based processing increased from ages 6 to 8 with no further developmental improvement, whereas recollection-based processing showed a longer trajectory, increasing into adolescence. Hence, these data generally indicate relatively rapid development of familiarity but comparatively prolonged maturation of recollection.

Although, as noted, the behavioral results of the current study support dual-process accounts of recognition memory, they differ from previous studies with respect to the question of when familiarity-related processes reach maturity. Unlike the results of the studies reviewed above, in the current data the familiarity estimates were lower in children and adolescents relative to young adults. In fact, children demonstrated the lowest estimate of familiarity-based responding compared to the 3 other groups, although the difference was only significant when contrasted with young adults (Table 3). This discrepancy in comparison to earlier studies might, perhaps, be due to the nature of the stimuli that were used here. Prior studies employed meaningful stimuli, the majority of which most likely had representations in long-term semantic memory. By contrast, the current investigation used pre-experimentally unfamiliar and, at least initially, unnamable symbol-like objects. Hence, the current data suggest that familiarity may not be fully mature in 9-10 year-old children, at least for material without initial semantic meaning. However, this suggestion is tempered by the lack (to the best of our knowledge) of developmental and/or age-related data in which the “meaningfulness” of the stimulus materials has been manipulated.

The findings from recent cognitive-aging reports suggest that the age-related hypothesis that recollection is impaired while familiarity is maintained may require revision – some studies have also observed age-related decrements in familiarity (Duarte, et al., 2006; Healy, Light, & Chung, 2005; Prull, et al., 2006; Toth & Parks, 2006). In the current study, as expected from previous work, older, relative to young, adults produced lower estimates of recollection. However, by contrast with many prior behavioral investigations (for review, see Light, Prull, Voie, & Healy, 2000), older relative to young adults also produced lower estimates of familiarity-based recognition. Hence, on the basis of the current R/K judgment data, our behavioral findings suggest a tighter fit with studies indicating that both recollection and familiarity diminish with aging than with those suggesting a selective age-related deficit in recollection. On the other hand, there is behavioral evidence suggesting that whether or not familiarity shows an age-related decrement is impacted by the model one uses to compute the familiarity estimates, whereas the well-replicated decrement in recollection does not appear to be model dependent (Healy, et al., 2005). Hence, the inconsistency in the age-related estimates of familiarity indicates clearly that further research is needed.

ERP Data

Familiarity-Based Processes –The Mid-Frontal EM Effect—As described earlier, a body of evidence suggests that the mid-frontal EM effect reflects acontextual, familiarity-based retrieval processes (reviewed in Rugg & Curran, 2007; but see discussion below). In the current data, the mid-frontal effect did not differ in magnitude among adolescents, young and older adults. Hence, based on the accumulated evidence, the current findings suggest that young and older adults as well as adolescents used familiarity-based processes in making their recognition decisions. Moreover, the putative neural correlate of familiarity did not change in magnitude across test phases for any of these three groups. These findings are in line with a previous study in which young and older adults showed reliable mid-frontal EM effects that did not vary in amplitude across two study/test phases (Nessler, et al., 2007)². Therefore, although the behavioral estimates of familiarity were lower in adolescents and older compared to young adults, the current ERP data suggest that the recruitment of familiarity-based processes may have matured to relatively adult-like levels by adolescence and are maintained into older age.

However, if familiarity-based processes are, to some extent, reflected in the mid-frontal EM effect, the absence of this effect in children is difficult to reconcile with the behavioral results of the current study, as well as behavioral data from previous studies indicating that pre-school age children (Anooshian & Seibert, 1996; Mandler, 2008) and those within the age range of the current study (Billingsley, et al., 2002; Ghetti & Angelini, 2008; Ofen, et al., 2007) are able to use familiarity-based processes to make recognition-memory decisions. On the other hand, the children of the current investigation, relative to adolescents and young adults, showed conservative decision criteria which did not vary across test phases. They also demonstrated a lower estimate of familiarity-based responding, relative to young adults, when independence between R and K judgments was assumed. Thus, children may be less flexible, in certain situations, in the differential recruitment of familiarity and recollection. These findings could be interpreted to mean that, despite their overall poorer performance, the majority of correct recognition decisions was made on the basis of recollection, resulting in reliable early-onset, 300-500 ms and subsequent, 500-700 ms parietal effects, a smaller number of familiarity-based decisions, and the absence of a mid-frontal EM effect (see also Czernochowski, et al., 2005). That is, the strict response criterion (only saying old when one is relatively certain) could have indicated that the children judged items as old only when they had sufficient contextual information available to inform that judgment. However, given the assumption of the independence model, one would expect a good proportion of recollected items to also be accompanied by familiarity. By this argument, if the mid-frontal EM effect reflects familiarity processing in all age groups, we would have expected to see some evidence of this effect in the children of the current study.

The lack of mid-frontal EM effects in children between 9 and 10 years of age also receives support from unpublished observations and a new analysis of the data obtained in the ERP developmental study by Cycowicz, et al. (2003). In highly similar fashion to the current results and those of Czernochowski and colleagues (Czernochowski, et al., 2005; Czernochowski, Mecklinger, & Johansson, 2009), mid-frontal EM effects were not reliable for either target old or non-target old items in the 9-10 year-old children, but were in adolescents and young adults³. These and the extant data reviewed above suggest the possibility that the neural correlates of familiarity-based processing in children have not yet been uncovered. Thus, there is a pressing need for further work to determine the circumstances under which the mid-frontal

²Older adults displayed a right-frontal scalp distribution in the current study (Figure 2) and the Nessler, et al. (2007) investigation. However, we believe that, although the distribution is somewhat different in older adults, the cognitive phenomena reflected by this activity are synonymous with those of the mid-frontal EM effect. For example, as noted in the text, in the current and Nessler, et al. (2007) data, this activity in older adults was not influenced by repetition, in highly similar fashion to the mid-frontally distributed effect in adolescents and young adults.

(and possibly other) familiarity-related memory effects are observed in developmental samples.

By contrast, the evidence in favor of the hypothesis that the mid-frontal EM effect reflects familiarity has been contested by other theorists whose data and arguments suggest that conceptual priming is the likely candidate (Paller, et al., 2007). In a very recent investigation that attempted to adjudicate between these two positions, the results offered strong support for the familiarity-based hypothesis (Stenberg, et al., 2008 but see Lucas, Voss, & Paller, 2009). Nonetheless, using initially unnamable and pre-experimentally unfamiliar, symbol-like stimuli, the data of de Chastelaine, et al. (2009) suggest that neither conceptual priming nor familiarity can account fully for the processes that are reflected by this EM effect. Furthermore, data from primate models indicate that familiarity-based responding occurs quite early, at approximately 100 ms post-stimulus (Brown, 1996). On this view, the mid-frontal EM effect could reflect familiarity-driven processes indirectly, but these would occur downstream from the initial, early-onsetting neural events (Tsivilis, Otten, & Rugg, 2001). Hence, at the current stage of knowledge, it is difficult to come to definitive conclusions concerning the functional significance of the mid-frontal EM effect.

Recollection-Based Processes – The Parietal EM Effect—Unlike the contentious link between familiarity-based processing and the mid-frontal EM effect, a general consensus holds that recollection-based processes are reflected by the parietal EM effect (Paller, 2004; Rugg & Yonelinas, 2003; Wilding, 2000). The finding that children, adolescents and young adults produced reliable parietal EM effects that grew in magnitude as a function of test phase suggests the conclusion that these groups engaged in recollection-based processes that were incremented by repetition. Moreover, in the adolescents and young adults, the mid-frontal scalp distribution of the 300 - 500 ms interval observed during Tests 1&2 changed to one with a parietal focus in Tests 3&4, suggesting that the parietal EM effect overlapped temporally the frontal EM effect during Tests 3&4. This notion was supported by the onset analyses showing that the parietal oldnew difference occurred earlier as a function of repetition in children (who showed a reliable early-onset parietal effect in Tests 3&4), adolescents and young adults. In turn, this pattern of findings suggests that repetition led to earlier onsetting recollection-based processing, as concluded by de Chastelaine, et al. (2009), who based their interpretation solely on the data of the young adults of this investigation. Thus, the facilitated, presumably recollection-driven processes afforded by repetition, appear to occur in both children and adolescents.

By contrast, but consistent with models of the cognitive aging of episodic memory, older adults showed dramatically reduced signs of recollection-based processes. Surprisingly, unlike the data reported by Nessler, et al. (2007; reviewed in the Introduction), the presumed ERP correlate of recollection was not enhanced by repetition. This was so despite the fact that the symbol-like objects were repeated a total of 8 times (i.e., by the fourth test block) in the current study, whereas in Nessler, et al. (2007) the verbal items were only repeated a maximum of four times (i.e., by the second test block). One possibility for this difference is the difficult-to-name and unfamiliar nature of the stimuli used here. In Nessler, et al. (2007), participants encoded nouns, which typically have strong representations in long-term semantic memory. Hence, these stimulus events could have been elaborated semantically to ensure a fair amount of success during the subsequent recognition phase. Here, on the other hand, it would have been

³The Age Group (children, adolescents, young adults) by Trial Type (target old, nontarget old, new other or CR) ANOVA on the averaged voltage data (300-500 ms) recorded at Fz revealed a main effect of Trial Type ($F(2,90) = 9.98, P < 0.0001, \epsilon = 0.94, \eta p^2 = 0.18$; Age Group $\times$ Trial Type $F = 1.26$). However, planned comparisons indicated that adolescents ($F(2,30) = 4.78, P < 0.02, \epsilon = 0.99, \eta p^2 = 0.24$) and young adults ($F(2,30) = 24.83, P < 0.0001, \epsilon = 0.91, \eta p^2 = 0.62$), but not children ($F = 1.15$) showed main effects of Trial Type. For adolescents and young adults, post-hoc tests indicated that target and nontarget old items differed reliably from CRs but not from each other, indicating robust mid-frontal EM effects.

difficult, at least initially, to attach a semantic label to these stimulus events. Indeed, the older adults of Nessler, et al. (2007) showed greater memory sensitivity values in Test 1 ($Pr = 0.59$) and Test 2 ($Pr = 0.82$) than those shown here in Tests 1&2 ($Pr = 0.32$) and Tests 3&4 ($Pr = 0.58$), the latter value appearing equivalent to the sensitivity index derived from the Test 1 data of Nessler, et al. (2007). This comparison confirms the greater difficulty older adults encountered in recognizing previously studied symbol-like objects in the current paradigm. Hence, on this basis, it could be tentatively concluded that the older adults had little contextual detail with which to render recollection-based judgments, thereby resulting in a reduction in the parietal EM effect.

However, an alternative explanation is possible. Re-inspection of Figures 1 and 2 shows that, during the period of the parietal EM effect (500-700 ms) at both Tests 1&2 and 3&4 over left fronto-central scalp sites, older adults (by contrast with the other 3 groups) showed greater *negative-going* activity to hits than CRs (Figure 2 - fourth row of maps). This suggests that the negative-going activity overlapped the parietal EM effect, thereby potentially reducing its amplitude during both test phases. This negative activity could reflect processes different from those used by young adults, children and adolescents. These might be brought on line when, perhaps due to impoverished encoding (Nessler, Johnson, Bersick, & Friedman, 2006), recognition decisions cannot be supported by recollection (Nessler, et al., 2007; see also Duarte, et al., 2006; Li, et al., 2004, and Swick, et al., 2006). For example, in the study by Nessler, et al. (2007), although older adults showed evidence of, at least some, recollection-based processing following repetition (i.e., a reliable parietal EM effect evident only in Test 2 but not Test 1), this processing was still markedly reduced relative to that of young adults. Therefore, because the parietal EM effect and the left-frontal negativity were temporally coincident and both occurred prior to mean RT, Nessler, et al. (2007) tentatively concluded that the left-frontal negativity could have reflected processes that were instrumental in the older adults' recognition decisions.

On the other hand, it is possible that only a subset of older adults may need to recruit alternative retrieval processes (and putative brain networks). Further, the presence of the left-frontal negativity in the current investigation adds some ambiguity to the interpretation of the left parietal old/new effect in the sample of older adults. Hence, we attempted to disentangle the parietal EM effect and the left-frontal negativity and, thereby, potentially obtain more information on the functional significance of the latter. In pursuit of this goal, the older adults were categorized according to their memory-sensitivity scores (Pr) across all 4 test blocks into low- ($M = 0.31$) and high- ($M = 0.62$) performing subgroups by dividing the sample at the mean.⁴ Importantly, these two subgroups did not differ significantly in mean age, years of education, IQ or modified Mini-Mental Status. Figure 3 depicts the grand mean waveforms for the two subgroups. T-tests from 0 performed on the old-new difference means indicated that the low- Pr subgroup produced a reliable left-frontal negativity ($P < 0.009$), whereas the high- Pr subgroup did not ($P > 0.50$). Moreover, the high- Pr subgroup generated reliable early (300-500 ms; $P < 0.004$) and late (500-700 ms; $P < 0.009$) parietal EM effects, whereas the low- Pr group did not ($P_s > 0.25$). These data must be considered preliminary, interpreted cautiously, and require replication with a larger number of participants. Despite these caveats, they suggest that the low- Pr subgroup showed less recollective activity than their high- Pr counterparts (parietal EM effect) and, as a result, may have had to recruit alternative retrieval processes (left-frontal negativity). The fact that the frontal negativity onset before the recognition decision (indicated by RT) suggests that, in the poor- Pr subgroup, the left-frontal negativity may have reflected processes recruited in an attempt to “compensate” for reduced recollective processing. Further, unlike much of the hemodynamic (e.g., Cabeza, Anderson, Locantore, &

⁴We thank an anonymous reviewer for suggesting this analysis.

McIntosh, 2002) and some ERP (e.g., Riis, et al., 2008) literature on “compensation,” these data argue that it is poor- rather than good-performing older adults who may be required to “compensate” (see also Duverne, Motamedinia, & Rugg, 2009, Colcombe, Kramer, Erickson, & Scalf, 2005, and Zarahn, Rakitin, Abela, Flynn, & Stern, 2007, for similar interpretations based on fMRI data).

Nonetheless, the nature of the processes reflected by the left-frontal negativity remains to be determined. Because this activity has typically been observed in source-memory paradigms, some have suggested that it reflects alternate retrieval strategies in older adults necessitated by the greater demands on control processes required to recover contextual information from stored memory traces (Czernochowski, Fabiani, & Friedman, 2008; Nessler, et al., 2007; Swick, et al., 2006; Wegesin, Friedman, Varughese, & Stern, 2002; see Li, et al., 2004 for an alternative proposal). The current data are not inconsistent with this suggestion, although uncertainty surrounds this hypothesis. It is also possible that, because the negativity appears to precede mean RT, it might reflect attentional mechanisms that enhance task-relevant stimulus features in the service of the recovery of prior experience. At this point, however, this notion is speculative. More work is needed to determine the nature of the cognitive activity reflected by the left-frontal negativity and how those processes impact age-related change in episodic memory.

Conclusions

The current findings indicate that, relative to young adults, 9-10 year-old children, adolescents and older adults appear able to use familiarity- as well as recollection-based processes in making recognition decisions. On the basis of these data, familiarity-based processes may be reflected in the mid-frontal EM effect for adolescents, young and older adults. It may be the case, however, that, for children, a different, not yet isolated, scalp-recorded neural event is a sign of familiarity. The increase, with repetition, in behavioral estimates of recollection and memory sensitivity in association with increments in the parietal EM effect, suggest that it reflects recollection-driven memory processes. While the results suggest that the processes reflected in the parietal EM effect may not change much between 9-10 and young adulthood, this tentative conclusion is tempered by the fact that the children produced reliably lower behavioral estimates of recollection-driven processing and significantly reduced memory sensitivity indices compared to young adults. Moreover, the onset latencies of the children's parietal effect were delayed relative to those of young adults. Consistent with much prior work, recollection-based processing appears to decline with aging, although poor-performing older adults might engage alternative processes (reflected by the left-frontal negativity) not recruited by their good-performing counterparts or the younger age groups to support their recognition-memory decisions. Taken as a whole, these data suggest that episodic-memory development reflects the increasingly flexible and interchangeable use of familiarity and recollection with a breakdown in the latter at older ages, perhaps restricted to a subset of poor-performing elderly adults.

EXPERIMENTAL PROCEDURE

Participants

Sixteen children (9-10 years of age, 7 female), 15 adolescents (13-14, 6 female), 18 young adults (20-25, 16 female) and 17 older adults (61-81, 12 female) participated. All spoke English as their first language. The study was approved by the Institutional Review Board of the New York State Psychiatric Institute. Adult volunteers and parents of child participants gave informed consent, while children signed assent forms. All volunteers were reimbursed for participating.

Neuropsychological Screening

The demographic and neuropsychological data for the four groups are presented in Table 6. Young and older volunteers were administered the Modified Mini-Mental Status examination (mMMS; Mayeux, Stern, Rosen, & Leventhal, 1981) and achieved a score within the normal range. IQ for the children and adolescents was obtained from the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1991). IQ for young adults was estimated from the Vocabulary and Block design subtests of the Wechsler Adult Intelligence Scale-III (Wechsler, 1997). Older volunteers were administered the full WAIS-III. All participants obtained IQ scores within the average to above average range.

In addition, older-adult volunteers underwent a semi-structured interview (SHORT CARE (Gurland, Golden, Teresi, & Challop, 1984) to ensure that they were free from dementia, depression, and not limited in the activities of daily living (see Table 6), as well as a medical and neurological examination. This examination was conducted by a board-certified neurologist in order to assess prospective volunteers for the presence of neurodegenerative disorders, clinically detectable neurovascular disease, disturbances in gait, visual acuity, and visual fields, and the presence of tremors or rheumatological disorders.

Stimuli

To assess the effects of study-test repetition on the putative ERP correlates of familiarity and recollection, we created study and test lists that were to be repeated four times as studied (old) items, but employed different lists of unstudied (new) items for each test list (de Chastelaine, et al., 2009). Critical stimuli consisted of 160 pre-experimentally unfamiliar symbols (see Figure 4), each of which was determined to be initially unnamable from the ratings of at least 8 out of 10 young-adult pilot participants who were not part of the experiment proper. Children, adolescents and older-adult volunteers did not participate in this pilot study (but, see the results of the post-experimental “naming” session in the Results section). From this pool of 160 symbols, 4 lists of 40 symbols were randomly chosen to be rotated across participants so that each list served approximately equally often as the study list. Thus, for each participant, the 4 study lists contained the same 40 symbols, although the symbols were randomly ordered for each study block. From the remaining pool of 120 symbols, 4 test lists were randomly assigned 30 symbols each to serve as new items. Thus, each test list contained 70 symbols which were randomly ordered for each participant. There were 4 additional filler symbols, of which 2 were added to the beginning and end of the study list. These 4 fillers were not included in the analyses.

Procedure

Participants were seated in a sound-damped and electrically-shielded room approximately 100 cm from a 17" display monitor on which the experimental stimuli were presented. Participants were informed that they would be taking part in a memory experiment consisting of 4 study/test blocks, and were given instructions for the Remember/Know procedure (Tulving, 1985). Instructions for this procedure were based on those used in previous research (Gardiner, 1988), although they were modified with concrete examples in order make the distinction between ‘Remember’ (hereafter, R) and ‘Know’ (hereafter, K) crystal clear for the younger volunteers. A rather lengthy and comprehensive procedure was engaged in prior to the experiment to ensure that children were using the two judgments appropriately. These instructions were quite detailed and included concrete examples of events in the childrens' own lives, for example, of times spent with friends and places visited in New York, as well as examples specific to the experiment itself. In each case, we checked the childrens' understanding by asking them to identify whether their recognition of these types of events was simply a ‘know’ memory or a ‘remember’ memory and then asked them to explain why. The instructions were repeated until the experimenters were sure that the child understood the

distinction. After finishing all 4 study/test blocks, participants completed a debriefing questionnaire.

Following the debriefing questionnaire, a 'symbol naming' task was administered in which the 40 old, symbol-like objects were re-presented one at a time on the computer monitor. For each symbol, participants were asked if it had reminded them of a familiar object and/or if they had 'named' this symbol at any point during the 4 study-test blocks. No time limits were imposed for this part of the experiment and each participant's responses were recorded verbatim.

All stimuli were presented in black outline within a centrally-located grey presentation box (500 × 500 pixels). Half of the study stimuli were presented to the left of and half to the right of center. Symbol-to-side of presentation mapping was randomly assigned, but remained invariant for each object across the 4 study blocks. Study and test trials consisted of the presentation of the stimulus for 500 ms, followed by a blank presentation box for 1500 ms.

Figure 4 provides an overview of the design (see de Chastelaine, et al., 2009, for complete details). For each study phase, participants were asked to memorize each symbol and its associated side of presentation (left or right) for a subsequent memory test. In order to ensure that they attended to the side of presentation, participants were asked to press the corresponding left- or right-hand button during stimulus presentation. For each test trial, subjects pressed one button for previously-studied symbols and the other for new symbols. The mapping of hand to old/new responses was rotated across participants and study-list assignment. When a participant responded 'new', the next symbol was presented. When an "old" response was indicated, participants made two additional judgments. One of these was a R/K judgment, which was cued by one of two types of display: 'Remember ? Know' or 'Know ? Remember'. The type of R/K cue was invariant for each participant but was rotated across participants, study-list assignment and old/new response type. Participants also decided if the symbol had been presented to the left or right of fixation during study, and the cue for this judgment was indicated by the instruction 'Left ? Right'.⁵ Participants indicated their choice by pressing the response button on the side indicated by the corresponding prompt. To prevent anticipatory responding, the Left/Right and R/K cues were randomly ordered.⁶ For all study and test trials, participants were asked to respond quickly and accurately. Responses faster than 300 ms or slower than 2000 ms were rejected. A practice study-test was administered prior to the first experimental block.

EEG recording

EEG was recorded with sintered Ag/AgCl electrodes mounted in an elastic cap (Neuromedical Supplies) from 62 scalp sites in accord with the extended ten-twenty system (Sharbrough, et al., 1990). Participants were grounded with an electrode placed on the right forehead.

⁵Hand of response always corresponded to the side (or source) on which the object had been presented during study, making it difficult to rule out the influence of response priming. Hence, it would not be clear whether correct source judgments reflected recollection or merely response priming. Therefore, because response priming might have been influenced by developmental and age-related differences, source (i.e., side of presentation) judgments were not analyzed here.

⁶It is possible that side of study could have influenced the proportion of Remember judgments that were generated, also via a response-priming mechanism. This was assessed independently of the order of the R/K and left/right source judgments during test and only for trials associated with Hits and correct left/right source judgments. We computed the percentage of trials in which an item was correctly recognized and followed by a Remember judgment (presented on the left/right at test) as a function of the number of trials presented on the left/right during study whose source was correctly judged (on the left/right during test). An Age Group × Study Presentation Side × Remember Judgment Side yielded an interaction of Study Presentation Side and Remember Judgment Side, but no main effect of or interactions with Age Group. The Study Presentation Side × Remember Judgment Side interaction indicated (as assessed by post-hoc tests) that there was an advantage when Study side and Remember side were both on the right ($M = 0.67$) compared to when they were both on the left ($M = 0.56$). Further post-hoc testing indicated that there was no difference in the percentage of Remember judgments when Study side and Remember side did not coincide ($M_s = 0.52$ and 0.54). The important point of this analysis is that, while there was a slight influence of response priming on the percentage of Remember judgments, the lack of age-group differences in this effect implies that age-group differences in recollective processing could not have been due to response priming.

Horizontal EOG was recorded from electrodes placed on the outer canthus of each eye and vertical EOG was recorded from electrodes placed above and below the left eye. Electrode impedance was kept below 5 kOhms. Eye movement artifacts were corrected off-line (Semlitsch, Anderer, Schuster, & Presslich, 1986) and trials with other visible artifacts (e.g., muscle artifacts) were rejected. If single channels showed artifacts, a spherical spline algorithm (Perrin, Pernier, Bertrand, & Echallier, 1989) was used to interpolate them on a trial-by-trial basis, with the constraint that not more than four channels were interpolated for a given trial (Picton, et al., 2000). The activity at all scalp electrodes was referenced to nose tip and re-referenced offline to averaged mastoids. EEG and EOG (DC; 100 Hz high-frequency cut-off; 500 Hz digitization rate) were recorded continuously with Synamp amplifiers. Data were epoched off-line with 100 ms pre- and 1100 ms post-stimulus intervals. To ensure a sufficient number of trials in each test condition to construct ERP averages, these were formed for correct responses to old and new items collapsed across the first two (hereafter **Tests 1&2**) and last two tests (hereafter **Tests 3&4**)⁷.

Data analyses

Behavioral and ERP data were analyzed using mixed design ANOVAs with the between-subjects factor of Age Group. F-ratios are reported with uncorrected degrees of freedom, corrected p-values and the epsilon (ϵ) value calculated to correct for non-sphericity (Jennings & Wood, 1976). Partial η^2 (ηp^2) is presented as an estimate of main and interaction effect sizes. Tukey HSD post-hoc tests were used to assess between-group main effects and, where appropriate, interaction effects. The construction of the ANOVAs is detailed in the corresponding results sections.

For the ERP data, the selection of latency regions and electrode sites was based on previous findings, as well as visual inspection of the grand average waveforms and scalp distributions of ERP EM effects. The waveforms associated with Hits and CRs in Tests 1&2 and Tests 3&4 were quantified by measuring the mean amplitude (relative to the pre-stimulus baseline) over two consecutive latency regions, 300-500 and 500-700 ms, putatively associated with, respectively, familiarity and recollection.

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Figure 1.

Grand mean waveforms associated with hits and CRs in Tests 1&2 and Tests 3&4 for children and adolescents (**1A**) and young and older adults (**1B**). The data are depicted at the midline Fz site where the mid-frontal EM effect was largest in children, adolescents and young adults. The data at F3 and F4 are also illustrated, because older adults showed greater negative-going activity to Hits than CRs at the F3 scalp site and the largest magnitude mid-frontal EM effect at F4. ERP waveforms are also depicted at left (P3), midline (Pz) and right (P4) parietal scalp locations (all age groups) to illustrate the early-onset and subsequent parietal EM effects. Light gray shading denotes the mid-frontal EM effect, black shading the early-onset parietal effect, dark gray shading the parietal EM effect, and cross hatching the left-frontal negativity observed only in older adults. Note that, in order to demonstrate the negative-going ERP effects for older adults, the scale has been increased for this group. Arrows mark stimulus onset, with timelines every 300 ms.

Figure 2.

Scalp topographies of the 300-500 ms and 500-700 ms regions (based on the Hit-CR difference means) putatively reflecting, respectively, familiarity- and recollection-based processes. The two left-hand columns represent Tests 1&2 and the two right-hand columns, Tests 3&4. For the children, note that the mid-frontal scalp map is not depicted for the 300-500 ms region (top left), as the difference between old and new items was not reliable (see text). Note also the different calibrations (Δ mV) to the right of the scalp maps for each of the four age groups. Unshaded regions reflect positivity; shaded regions reflect negative activity.

Figure 3.

Grand mean waveforms associated with hits and CRs (across all 4 test blocks) for older-adult participants in the High- and Low-Pr subgroups. The early-onset and subsequent parietal EM effects are shaded, respectively in black and gray fill. Cross hatching indicates the left-frontal negativity which was reliable in the Low-Pr but not the High-Pr subgroup. Arrows mark stimulus onset, with timelines every 300 ms.

Figure 4.
Schematic of the experimental paradigm showing both study and test trials.

Table 1

Mean Percentage Correct, Pr and Br, and Reaction times ($\pm$ SE) for Tests 1&2 and Tests 3&4 for the Four Age Groups.

Age Group	Test Phase	Accuracy, Sensitivity and Response Bias				Reaction Time	
		% Hits	% CRs	Pr	Br*	Hits	CRs
Children	Tests 1&2	41.4 (3.7)	80.1 (2.7)	0.26 (0.04)	.20 (.03)	725 (41)	693 (44)
	Tests 3&4	60.8 (5.3)	88.2 (2.2)	0.51 (0.06)	.18 (.03)	710 (43)	674 (44)
Adolescents	Tests 1&2	51.1 (3.1)	74.8 (3.5)	0.35 (0.04)	.23 (.04)	626 (32)	623 (32)
	Tests 3&4	72.6 (3.2)	82.7 (3.2)	0.59 (0.05)	.30 (.03)	587 (22)	600 (13)
Young Adults	Tests 1&2	66.7 (3.5)	85.2 (2.6)	0.54 (0.03)	.30 (.05)	712 (28)	754 (25)
	Tests 3&4	92.7 (1.3)	89.8 (1.5)	0.83 (0.02)	.56 (.05)	655 (32)	688 (23)
Older Adults	Tests 1&2	61.4 (5.0)	70.5 (4.5)	0.32 (0.04)	.44 (.06)	979 (39)	998 (47)
	Tests 3&4	78.0 (4.6)	80.6 (3.7)	0.58 (0.04)	.50 (.09)	895 (35)	913 (40)

Notes: Hits = correctly recognized old items; CRs = correctly rejected new items; Pr (sensitivity) = $P_{hit} - P_{false alarm}$; Br (response bias) = $(P_{false alarm}) / (1 - (P_{hit} - P_{false alarm}))$;

* For Br, values < 0.5 = conservative bias; > 0.5 = liberal bias (Snodgrass & Corwin, 1988).

Table 2
Mean Proportion of R and K Judgments ($\pm$ SE) Associated with Old and New Items for each Test Phase and Age Group.

Age Group	Test Phase	R Old	K Old	R New	K New
Children	Tests 1&2	0.22 (.04)	0.20 (.04)	0.06 (.02)	0.08 (.02)
	Tests 3&4	0.36 (.06)	0.24 (.05)	0.02 (.01)	0.06 (.02)
Adolescents	Tests 1&2	0.30 (.03)	0.23 (.03)	0.06 (.01)	0.09 (.02)
	Tests 3&4	0.46 (.05)	0.27 (.05)	0.03 (.01)	0.07 (.02)
Young Adults	Tests 1&2	0.33 (.05)	0.34 (.03)	0.02 (.01)	0.10 (.02)
	Tests 3&4	0.62 (.06)	0.31 (.05)	0.02 (.01)	0.06 (.01)
Older Adults	Tests 1&2	0.29 (.05)	0.32 (.05)	0.10 (.02)	0.19 (.03)
	Tests 3&4	0.39 (.07)	0.39 (.06)	0.04 (.01)	0.15 (.03)

Table 3

Mean ($\pm$ SE) adjusted R and K estimates for each Test Phase and Age Group based on the data in Table 2.

Age Group	Test Phase	R adjusted	K adjusted
Children	Tests 1&2	0.15 (.04)	0.16 (.04)
	Tests 3&4	0.35 (.06)	0.31 (.06)
Adolescents	Tests 1&2	0.24 (.03)	0.22 (.04)
	Tests 3&4	0.42 (.05)	0.40 (.07)
Young Adults	Tests 1&2	0.31 (.04)	0.41 (.03)
	Tests 3&4	0.60 (.06)	0.66 (.06)
Older Adults	Tests 1&2	0.19 (.04)	0.22 (.04)
	Tests 3&4	0.35 (.06)	0.47 (.06)

Notes. R = Remember; K = Know.

Table 4

Grand mean ($\pm$ SE) Difference Amplitudes (in μ V) between Hits and CRs for the 300-500 ms window in Tests 1&2 and 3&4 at Fz and F4 (mid-frontal EM effect), and P3 (early-onset parietal effect) for each of the Four Age Groups.

300-500 ms	Electrode	Tests 1&2	Tests 3&4
Children	Fz	-1.0 (1.4)	1.8 (1.0)
	F4	-0.8 (1.5)	0.9 (0.9)
	P3	0.2 (0.8)	4.6 (1.6)*
Adolescents	Fz	3.7 (1.0)*	4.1 (0.7)*
	F4	3.0 (1.0)*	2.5 (0.5)*
	P3	1.4 (0.7)*	3.1 (0.7)*
Young Adults	Fz	3.2 (0.5)*	3.2 (0.5)*
	F4	2.8 (0.6)*	2.7 (0.5)*
	P3	1.7 (0.5)*	3.2 (0.5)*
Older Adults	Fz	1.0 (0.3)*	1.2 (0.5)*
	F4	1.3 (0.2)*	1.1 (0.5)*
	P3	0.3 (0.3)	0.7 (0.4)

Notes.

* Indicates that the difference between Hits and CRs was reliable at $P < 0.05$ or better via t-test.

Table 5

Grand mean ($\pm$ SE) Difference Amplitudes (in μ V) between Hits and CRs for the 500-700 ms window in Tests 1&2 and 3&4 at P3 and Pz (parietal EM effect) for each of the Four Age Groups.

500-700 ms	Electrode	Tests 1&2	Tests 3&4
Children	P3	5.1 (1.2) *	10.4 (1.6) *
	Pz	8.7 (1.4) *	15.0 (1.7) *
Adolescents	P3	6.0 (0.9) *	7.3 (1.1) *
	Pz	6.2 (0.9) *	8.4 (0.9) *
Young Adults	P3	4.4 (0.7) *	5.1 (0.7) *
	Pz	4.5 (0.6) *	4.9 (0.9) *
Older Adults	P3	1.0 (0.4) *	1.5 (0.5) *
	Pz	1.1 (0.5) *	1.0 (0.5) *

Notes.

* Indicates that the difference between hits and correct rejections was reliable at $P < 0.05$ or better via t-test.

Table 6Demographic and Neuropsychological Test Results ($\pm$ SD) for the Four Groups of Participants

	Children	Adolescents	Young Adults	Older Adults
	N = 6	N = 15	N = 18	N = 17
Age	10.0 (0.6)	14.0 (0.5)	23.2 (1.6)	70.3 (6.5)
Education	4.2 (0.6)	9.5 (0.7)	16.2 (1.2)	16.4 (2.5)
Laterality Quotient [‡]	63.1 (49.7)	65.7 (39.4)	88.3 (15.6)	91.6 (13.9)
SES	£48.4 (26.5)	£50.9 (26.0)	55.9 (12.7)	38.0 (21.1)
Performance IQ [¶]	120.3 (14.4)	105.7 (18.7)	115.6 (14.9)	118.6 (9.9)
Verbal IQ [¶]	126.6 (14.5)	116.0 (14.8)	132.8 (13.9)	129.3 (13.7)
mMMS [§]	NA	NA	55.1 (2.3)	55.1 (1.3)
Digits Forwards	6.6 (1.2)	7.1 (1.8)	7.6 (1.3)	7.5 (0.9)
Digits Backwards	4.6 (1.2)	5.8 (0.9)	5.7 (1.3)	5.5 (1.2)
CARE Depression [§]	NA	NA	NA	1.4 (1.7)
CARE Dementia [§]	NA	NA	NA	0.1 (0.2)

Notes.

NA = not applicable;

[§] mMMS = modified mini-mental status exam (Mayeux, et al., 1981); maximum score = 57; SES = socio-economic status (higher score = lower SES; (Watt, 1976);

[£] based on a score averaged across the SES values for the child's mother and father.

[‡] Measured according to (Oldfield, 1971);

[¶] WAIS-III (Wechsler, 1997) for young and older adults; WISC-III for children and adolescents;

[§] From the Short Care (Gurland, et al., 1984); cutoff is 6 for depression and 7 for dementia.