Effects of Age on the Neural Correlates of Familiarity as Indexed by ERPs

Tracy H. Wang, Marianne de Chastelaine, Brian Minton, and Michael D. Rugg

Abstract

ERPs were recorded from samples of young (18–29 years) and older (63–77 years) participants while they performed a modified “remember–know” recognition memory test. ERP correlates of familiarity-driven recognition were obtained by contrasting the waveforms elicited by unrecollected test items accorded “confident old” and “confident new” judgments. Correlates of recollection were identified by contrasting the ERPs elicited by items accorded “remember” and confident old judgments. Behavioral analyses revealed lower estimates of both recognition and familiarity in older participants than in young participants. The putative ERP correlate of recollection—the “left parietal old–new effect”—was evident in both age groups, although it was slightly but significantly smaller in the older sample. By contrast, the putative ERP correlate of familiarity—the “midfrontal old–new effect”—could be identified in young participants only. This age-related difference in the sensitivity of ERPs to familiarity was also evident in subgroups of young and older participants, in whom familiarity-based recognition performance was equivalent. Thus, the inability to detect a reliable midfrontal old–new effect in older participants was not a consequence of an age-related decline in the strength of familiarity. These findings raise the possibility that familiarity-based recognition memory depends upon qualitatively different memory signals in older and young adults.

INTRODUCTION

There is substantial evidence that recognition memory can be supported by two different processes, usually termed familiarity and recollection. In what is probably the most widely accepted “dual-process” account of recognition memory (Yonelinas, 1994, 2001; see Yonelinas & Parks, 2007; Diana, Reder, Arndt, & Park, 2006, for reviews of this and several other models), these processes are held to be computationally distinct and to act independently. According to this account, familiarity reflects an acontextual, continuous memory signal that does not provide qualitative details about the study episode. By contrast, recollection has a threshold-like character and involves retrieval of consciously accessible details of the study event (see Wixted & Mickes, 2010, for an alternative account in which recollection, like familiarity, is assumed to depend on a continuous signal).

Numerous studies have investigated the effects of advancing age on recognition memory performance from the dual-process perspective (see Yonelinas, 2002, for a review; for examples of more recent studies, see McCabe, Roediger, McDaniel, & Balota, 2009; Howard, Bessette-Symons, Zhang, & Hoyer, 2006; Prull, Dawes, Martin, Rosenberg, & Light, 2006; Bastin & Van der Linden, 2003). Although there is a strong consensus that recollection declines with increasing age (e.g., Bugaiska et al., 2007; Howard et al., 2006; Prull et al., 2006; Healy, Light, & Chung, 2005; Bastin & Van der Linden, 2003; Parkin & Walter, 1992; for a review, see Yonelinas, 2002), there is less consensus about familiarity. Whereas some studies have reported that familiarity estimates do not vary with age (e.g., Howard et al., 2006; Mark & Rugg, 1998; Jennings & Jacoby, 1997; Perfect, Williams, & Anderton-Brown, 1995; Parkin & Walter, 1992), other studies reported age-related decrements (e.g., Parks, 2007; Duarte, Ranganath, Trujillo, & Knight, 2006; Toth & Parks, 2006; Perfect & Dasgupta, 1997). In one recent study, the effects of age on familiarity estimates depended on the test procedure used to operationalize and estimate familiarity (Prull et al., 2006). Although the reasons for these divergent findings are currently unclear, the findings raise the possibility that that familiarity-based recognition depends on multiple processes or sources of information, some of which are more vulnerable to advancing age than others.

The foregoing behavioral studies addressed the question of whether recollection- and familiarity-driven recognition memory are differentially impaired as a function of age, as evidenced by age-related differences in the accuracy of different classes of memory judgment assumed to largely depend on one or the other memory process (e.g., “remember” vs. “know” judgments, see below). A complementary question asks not whether memory performance differs quantitatively according to age but whether it differs qualitatively. Thus, this question focuses on whether there are age-related changes in the computational or informational bases of recollection or familiarity. Unlike...
the prior question, which is necessarily addressed at the behavioral level, it is arguable that this second question is most amenable to investigation with methods that identify and contrast the neural correlates of recollection and familiarity. According to this logic, if the neural correlates of successful recognition memory do not differ with age or differ only quantitatively, this would suggest that the processes supporting recognition judgments are age-invariant. By contrast, if the neural correlates of recognition differ qualitatively with age (that is, in a manner suggesting the engagement of different neural populations), this raises the possibility that the nature of the processes supporting recognition changes with age, potentially shedding light on any corresponding differences in recognition performance.

In the present study, we addressed this question using scalp-recorded ERPs to identify and contrast the neural correlates of recollection and familiarity in groups of young and older participants.

The present study builds on extensive evidence that ERP effects elicited in young participants by test items recognized on the basis of familiarity or recollection differ in their temporal properties and scalp distributions (for reviews, see Rugg & Curran, 2007; Mecklinger, 2006; Friedman & Johnson, 2000). Both classes of effect take the form of a positive-going ERP modulation relative to ERPs elicited by correctly rejected new items. However, whereas recognition on the basis of familiarity is associated with a relatively early (ca. 300–500 msec), frontally distributed “old–new” effect (the “midfrontal” old–new effect, also termed as the “FN400”), recognition on the basis of recollection is reflected by a later effect (ca. 400–800 msec) that is often maximal over the left parietal scalp (the “left parietal” old–new effect). In recent studies, in which nonrecalled test items were segregated according to their familiarity strength (operationalized by recognition confidence; Yu & Rugg, 2010; Woodruff, Hayama, & Rugg, 2006), the midfrontal effect was reported to vary monotonically with familiarity strength, but also to be insensitive to whether an item was endorsed as recollected. The left parietal old–new effect, by contrast, was insensitive to familiarity strength and varied, instead, according to whether the test item was endorsed as recollected. These ERP effects arguably constitute a double dissociation between the neural correlates of familiarity and recollection.

In parallel with research on neural correlates of recognition memory in young participants, a substantial literature has developed, which compares these ERP correlates across groups of young and older participants (for reviews, see Cansino, 2009; Friedman, Nessler, & Johnson, 2007; Friedman, 2000, 2003). A large proportion of these studies employed test procedures that did not permit ERPs to be segregated according to whether the eliciting test items were recognized on the basis of recollection or familiarity (e.g., Friedman, de Chastelaine, Nessler, & Malcolm, 2010; Guillaume et al., 2009; Wolk et al., 2009; Ally, Waring, McKeever, Milberg, & Hudson, 2008; Wegesin, Friedman, Varughese, & Stern, 2002; Fabiani & Friedman, 1997).

Hence, these studies cannot speak directly to the question of whether the ERP correlates of the two memory processes differ according to age. Of those studies that did segregate ERPs according to whether trials were associated with recollection or familiarity, some focused solely on ERP correlates of recollection (e.g., Li, Morcom, & Rugg, 2004; Mark & Rugg, 1998; but see also Duarte et al., 2006; Wegesin et al., 2002; Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999). It has been reported that the recollection-related left parietal old–new effect, although often delayed in onset (e.g., Duarte et al., 2006; Wegesin et al., 2002; Trott et al., 1999; Mark & Rugg, 1998) and, in one study, smaller in magnitude in older relative to young participants (Trott et al., 1999), does not qualitatively differ with age (i.e., its scalp distribution is age-invariant). Such findings support the proposal (e.g., Mark & Rugg, 1998) that age-related decrements in recollection are largely the result of factors that impact the probability of successful recollection and that the processes (or more correctly, those processes indexed by ERPs) engaged when recollection is successful are little affected by age.

Few studies have investigated the effects of age on the putative ERP correlate of familiarity—the midfrontal effect. To our knowledge, to date, there are only two published studies in which the effects of age on the midfrontal effect were investigated in the context of a retrieval test that segregated familiarity- and recollection-driven recognition judgments (Duarte et al., 2006; Trott et al., 1999). Trott et al. recorded ERPs at test to sequentially presented noun pairs, each word within the pair requiring a speeded “old–new” judgment. Subsequent to the two judgments, words judged old were re-presented for both a source memory judgment (which of two study lists did the word belong to?) and a “remember–know” judgment (when participants are instructed to endorse items as “remembered” if recognition is accompanied by recollection of one or more study details and “know” if recognition is based solely on a sense of familiarity). In the young participant group, a reliable midfrontal effect was elicited by both items endorsed as “know” and items attracting an incorrect source. By contrast, these classes of test item both failed to elicit a reliable effect in older participants. In the study by Duarte et al. (2006), ERPs were elicited by studied and unstudied items (grayscale pictures) during a “remember–know” test. The authors reported that, although a robust midfrontal old–new effect—operationalized by the contrast between ERPs elicited by test items accorded a “know” judgment versus items incorrectly judged new (misses)—was reliable in the young participant group, the effect was absent in the older participants.

The findings of Duarte et al. (2006) and Trott et al. (1999) raise the possibility that the neural (and, presumably, the cognitive) bases of familiarity-driven recognition memory change with increasing age. These findings are participant to an important caveat, however. Although familiarity strength was not estimated by Trott et al. (1999), overall recognition memory was lower in their older...
participants than in their young participants. Duarte et al. (2006) computed familiarity estimates for the two age groups and reported that these estimates were significantly lower in the older participants. Thus, in both studies, age-related differences in the magnitude of the midfrontal old-new effect were confounded with differences in recognition memory performance. Because the magnitude of the effect covaries with familiarity strength (Yu & Rugg, 2010; Woodruff et al., 2006), it is possible that the failure of Duarte et al. (2006) to detect a reliable midfrontal effect in their older participants merely reflects a relatively small difference in the mean familiarity strengths of studied items accorded “know” and “new” judgments. The findings of Trott et al. (1999) might also be accounted for along similar lines.

In light of these possibilities, the present study revisited the question of whether ERP correlates of familiarity differ as a function of age. We employed a modified remember–know procedure identical to that used to segregate unrecalled test items according to their familiarity strength in prior studies (Yu & Rugg, 2010; Woodruff et al., 2006; Yonelinas, Otten, Shaw, & Rugg, 2005). In this procedure, participants respond “remember” when a test item elicits a subjective sense of recollection, but in the absence of recollection, they provide a rating of their confidence that the item is studied or unstudied rather than merely making a “know” or a “new” judgment. By forming ERPs only from items at the extremes of the distribution of familiarity strength (items accorded “confident old” and “confident new” judgments), contrasts of the ERP correlates of familiarity across age groups can largely (but not entirely; see Results section below) be unconfounded with age-related differences in the strength of the underlying familiarity signal.

METHODS

Participants

Twenty-five older participants (14 women) aged between 63 and 76 years (mean age = 70 years) and 27 young participants (19 women) aged between 18 and 28 years (mean age = 21 years) participated in the experiment at a compensation rate of $15/hr. Three young participants were excluded because of poor EEG quality. One young participant was excluded because the participant had too few trials in a critical response category. One older participant was excluded because of poor performance during the practice of the experimental task before the EEG session, whereas another fell asleep intermittently during the duration of the test. Two additional older participants were excluded because of the contribution of too few trials in a critical response category. The final group included in the data analysis comprised 21 older participants (13 women; mean age = 70 years) and 23 young participants (16 women; mean age = 21 years). Young participants were recruited from the University of California-Irvine (UCI) undergraduate community. Most of the older participants were recruited from the local community through newspaper advertisements and flyers. Additional older participants were recruited from the control cohort of the UCI Alzheimer’s Disease Research Center. All participants were right-handed, had normal or corrected-to-normal vision, and scored 26 or more on the Mini-Mental State Examination. Exclusion criteria included a history of cardiovascular disease (other than treated hypertension), a history of diabetes, psychiatric disorder, illness or trauma affecting the CNS, substance or alcohol abuse, and current or recent use of psychotropic medication. Additional exclusion criteria included a score on a standardized memory test of >1.5 SD below the age-appropriate norm or a low performance (>1.5 SD below norm) on two or more of the nonmemory tests on the neuropsychological test battery described below. Informed consent was obtained in accordance with the UCI Institutional Review Board guidelines.

Neuropsychological Testing

A standardized neuropsychological battery was administered to all participants on a separate day from the ERP session. The battery was intended to assess functioning across a broad range of cognitive domains (refer to Table 1 for a complete list).

Materials

Stimulus lists of 300 critical items were generated from a pool of 526 words that had been selected from the Medical Research Council Psycholinguistics Database (www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm; Wilson, 1988). The words were between three and nine letters in length (mean = 5.6, SD = 1.5) and had a frequency range of 0–50 (mean = 14.0, SD = 12.9) occurrences per million (Kucera & Francis, 1967). The study phase employed 150 words, along with two filler words at the beginning and two filler words at the end of the study list. For the test phase, the 150 words from the study list were intermixed with 150 new words. Two filler words were presented at the beginning of the test list and immediately following the midlist break (see below). There were an equal number of words that represented living and nonliving items for both study and test phases. Stimuli were displayed on a black background on an LCD monitor. All words were presented in black uppercase 30-point Helvetica font (subtending a minimum–maximum horizontal visual angle of 1.5°–3.2° and a vertical visual angle of 0.5°) within a solid, gray rectangle (3.5° × 3.8°). A fixation cross (+; 0.5° × 0.5°) was presented centrally within the rectangle during the ISIs. Words were presented in the same manner across study and test phases.

Experimental Procedure

Practice of both study and test phases was administered before the experiment proper (see below). Following the
practice phase, participants were fitted with an electrode cap and seated in a sound attenuated room facing the computer monitor.

Each study trial began with the presentation of a red fixation cross for 500 msec. A word replaced the fixation cross and remained on the screen for 1000 msec. The word was replaced by a black fixation cross for 1650 msec, followed by the onset of the next trial, giving an SOA of 3150 msec. The study session lasted approximately 8 min, and EEG was not recorded.

The study task required participants to make an animacy judgment to each word. Participants indicated their responses with their right and left index fingers, with response assignment counterbalanced across participants.

The practice session of the test phase was split into two sections. In the first section, participants were required to explain the basis of each of their R responses in a self-paced version of the retrieval task. This was done to ensure that there was a full understanding of the difference between an R and a “confident old” judgment. The second half of the practice session was presented in the manner of the experiment proper.

EEG Recording and Analysis

EEG was recorded continuously during the test phase from 29 silver–silver chloride electrodes embedded in an elastic cap (EasyCap; Herrsching-Breitbrunn, Germany; www.easycap.de). Electrode sites corresponded to the International 10–20 System (American Electroencephalographic Society, 1994) and included three midline sites (Fz, Cz, and Pz) and 13 homotopic (left–right) pairs of sites.

Table 1. Subject Characteristics by Age Group and Performance on Standardized Neuropsychological Tests

<table>
<thead>
<tr>
<th></th>
<th>Young Group</th>
<th></th>
<th>Older Group</th>
<th></th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Range</td>
<td>Mean (SD)</td>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>Age, years</td>
<td>21.0 (2.5)</td>
<td>18–28</td>
<td>70.3 (3.3)</td>
<td>63–76</td>
<td></td>
</tr>
<tr>
<td>Years of education</td>
<td>15.3 (2.1)</td>
<td>13–20</td>
<td>17.1 (2.5)</td>
<td>12–21</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Mini-Mental State Examination</td>
<td>29.7 (0.6)</td>
<td>28–30</td>
<td>29.1 (1.1)</td>
<td>27–30</td>
<td></td>
</tr>
<tr>
<td>CVLT immediate free recall</td>
<td>12.8 (1.7)</td>
<td>10–15</td>
<td>11.0 (3.0)</td>
<td>5–16</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>CVLT immediate cued recall</td>
<td>13.3 (1.8)</td>
<td>9–16</td>
<td>12.1 (2.3)</td>
<td>6–16</td>
<td>ns</td>
</tr>
<tr>
<td>CVLT delayed free recall</td>
<td>13.7 (1.7)</td>
<td>10–16</td>
<td>11.7 (2.7)</td>
<td>5–16</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>CVLT delayed cued recall</td>
<td>14.0 (1.9)</td>
<td>10–16</td>
<td>12.4 (2.5)</td>
<td>6–16</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>CVLT delayed recognition</td>
<td>15.5 (0.7)</td>
<td>14–16</td>
<td>15.1 (1.1)</td>
<td>13–16</td>
<td>ns</td>
</tr>
<tr>
<td>NYU paragraph immediate recall</td>
<td>7.8 (3.5)</td>
<td>2–14.5</td>
<td>7.3 (2.2)</td>
<td>3.5–11.5</td>
<td>ns</td>
</tr>
<tr>
<td>NYU paragraph delayed recall</td>
<td>11.2 (2.9)</td>
<td>5–16</td>
<td>9.5 (2.8)</td>
<td>5–13</td>
<td>ns</td>
</tr>
<tr>
<td>Forward/backward digit span</td>
<td>18.3 (3.5)</td>
<td>15–27</td>
<td>18.3 (4.6)</td>
<td>12–27</td>
<td>ns</td>
</tr>
<tr>
<td>Digit/symbol substitution test</td>
<td>65.7 (10.9)</td>
<td>52–89</td>
<td>48.6 (6.7)</td>
<td>36–59</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Trail making test A (sec)</td>
<td>25.1 (7.2)</td>
<td>16–38</td>
<td>29.9 (8.5)</td>
<td>21–57</td>
<td>ns</td>
</tr>
<tr>
<td>Trail making test B (sec)</td>
<td>49.2 (13.0)</td>
<td>27–71</td>
<td>68.5 (18.5)</td>
<td>38–104</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Letter fluency</td>
<td>41.2 (10.0)</td>
<td>27–58</td>
<td>42.3 (9.7)</td>
<td>23–58</td>
<td>ns</td>
</tr>
<tr>
<td>Category fluency</td>
<td>24.2 (6.3)</td>
<td>16–42</td>
<td>18.9 (3.9)</td>
<td>12–27</td>
<td>&lt;.005</td>
</tr>
<tr>
<td>WTAR raw</td>
<td>41.8 (4.6)</td>
<td>34–50</td>
<td>43.2 (4.5)</td>
<td>33–49</td>
<td>ns</td>
</tr>
</tbody>
</table>

CVLT = California Verbal Learning Test; NYU = New York University; WTAR = Wechsler Test of Adult Reading Full-Scale Intellectual Quotient.
(Fp1–Fp2, AF7–AF8, F3–F4, F5–F6, F7–F8, C3–C4, C5–C6, T7–T8, P3–P4, P5–P6, P7–P8, PO7–PO8, and O1–O2). Additional electrodes were affixed to the left and right mastoid processes, respectively, and a ground electrode was embedded in the cap at FCz. Vertical and horizontal EOG were recorded from electrode pairs situated above and below the left eye and on each outer canthus, respectively. Data were acquired with respect to a common Cz reference using a Contact Precision Instruments (London, United Kingdom; www.psylab.com) system at a 256-Hz sampling rate and an amplifier bandwidth of 0.01–40 Hz (−3 dB).

Before data acquisition, electrode impedances were adjusted to be under 5 kΩ and rechecked during each break period. EEG epochs (2048 msec in duration, including a 102-msec prestimulus baseline) were extracted off-line. The epoched data were downsampled to a 125-Hz sampling rate and referenced to averaged mastoids. Trials were excluded if they contained artifacts associated with a baseline shift of >40 μV or eye movement artifacts other than a blink. ERPs were averaged and smoothed with a 5-point moving-window filter at a cut-off of 19.4 Hz (−3 dB). Blink artifacts were corrected using a previously described linear regression method (see Henson, Rylands, Ross, Vuilleumier, & Rugg, 2004).

The principal analyses compared a group of 23 young participants to a group of 21 older participants. In all ANOVAs reported below, degrees of freedom associated with repeated measures factors were corrected for nonsphericity (Greenhouse & Geisser, 1959).

RESULTS

Neuropsychological Test Scores

Performance on the neuropsychological test battery is reported in Table 1. Older participants scored less well than young participants on immediate and delayed free recall and delayed cued recall. Differences between the groups on immediate cued recall, recognition, and the New York University did not reach significance. The scores of the older participants also did not differ significantly from those of the young participants on digit span, letter fluency, Trail making A, or the Wechsler Test of Adult Reading. The older participants were impaired, however, on Trail making B, digit symbol substitution, and category fluency.

Behavioral Performance

Behavioral performance on the memory task is shown in Table 2 as the proportion of old and new items assigned an R response or one of the four different confidence ratings. ANOVA of these data (factors of Group, Study Status, and Response Category) revealed an Age × Study Status × Response Category interaction $F(3.4, 141.3) = 6.46, p < .001$. Follow-up $t$ tests revealed this interaction to be driven by a greater proportion of R responses to old items in the young participants relative to the older participants ($t(42) = 3.87, p < .001$). Conversely, older participants were more likely than the young group to respond confident new ($t(42) = 4.32, p < .001$) and unconfident new ($t(42) = 2.94, p < .01$) to old items.

RTs (in Table 2) were collapsed across study status except in the case of R responses (very few new items were endorsed “R”). An ANOVA with factors of Age and Response Category revealed a main effect of Response Category $F(2.9, 119.7) = 84.6, p < .001$ and an Age × Response Category interaction $F(2.9, 119.7) = 4.31, p < .01$. Despite the presence of this interaction, follow-up pairwise $t$ tests failed to identify any response category in which RTs differed significantly according to age.

Estimates of familiarity were calculated by collapsing items in the confident old (CO) and unconfident old (UCO) response categories and calculating the proportion of items judged old on the basis of familiarity according to the assumption that recollection and familiarity are independent of one another $p(F) = (p(CO + UCO|old)/(1 − p(R|old))) − ((p(CO + UCO|new)/(1 − p(R|new)))$.

<table>
<thead>
<tr>
<th>Table 2. Experimental Task Performance by Age Group</th>
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<tbody>
<tr>
<td>$R$</td>
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<tr>
<td>-------</td>
</tr>
<tr>
<td><strong>Young Group</strong></td>
</tr>
<tr>
<td>Old</td>
</tr>
<tr>
<td>New</td>
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<tr>
<td>RT*</td>
</tr>
<tr>
<td><strong>Older Group</strong></td>
</tr>
<tr>
<td>Old</td>
</tr>
<tr>
<td>New</td>
</tr>
<tr>
<td>RT</td>
</tr>
</tbody>
</table>

$SD$s are in parentheses.

*R*Ts are presented collapsed across old–new status for confidence response conditions. R response RTs are presented for old items only (see text).
Yonelinas & Jacoby, 1995]. Familiarity estimates were found to be lower in the older participant group than in the young participant group (young: mean = 0.65, older: mean = 0.49; \( t(42) = 4.44, p < .001 \)). Corrected recollection estimates \( p(R) = (p(R|\text{old}) - p(R|\text{new})) \) were also significantly lower in the older group than the young (young: mean = 0.35, older: mean = 0.22; \( t(42) = 4.17, p < .001 \)). Additionally, we calculated the accuracy associated with highly confident “old” and “new” judgments (cf. Wixted, Mickes, & Squire, 2010), the response categories employed for the key ERP analyses reported below. Mean accuracy of the old judgments (Confident Hit/(Confident Hit + Confident False Alarm)) was 0.92 for the young participants and 0.82 for the older group. These means differed significantly \( t(42) = 4.87, p < .001 \). The accuracy of new judgments (Confident Correct Rejection/Confident Correct Rejection + Confident Miss) also differed significantly, with means of 0.94 for the young participants and 0.88 for the older group \( t(42) = 3.67, p < .001 \). Thus, the strength of the memory signal supporting highly confident, familiarity-driven recognition judgments was lower in the older participants.

**ERP Results**

Grand-averaged ERPs from lateral frontal and parietal electrode sites are illustrated in Figures 1 (young participants) and 2 (older participants). In the case of the young participants’ ERPs, an old–new effect (the midfrontal effect), elicited by items endorsed either as recollected or highly familiar, is evident at frontal sites between around 300 and 500 msec. A later-onsetting parietal effect (the left parietal effect), elicited predominantly by recollected items, is also evident. Whereas the latter effect is also
evident in the ERPs from the older group, the earlier midfrontal effect is not discernable in these participants.

ERPs were initially quantified by computing the mean amplitude (with respect to the prestimulus baseline) of two consecutive latency regions: 300–500 and 500–800 msec poststimulus onset. These regions were selected a priori on the basis of prior studies to capture familiarity- and recollection-related effects, respectively (e.g., Yu & Rugg, 2010; Duarte et al., 2006; Woodruff et al., 2006). In the case of familiarity effects, we focused on the contrast between ERPs elicited by items accorded confident old versus confident new responses, because these two response categories represent the extremes of familiarity strength. For the analysis of recollection effects, we contrasted items receiving R responses (recollected items) with items endorsed as confident old and confident new. As in the case of the RT data, ERPs elicited in association with each confidence rating were formed from items collapsed across study status (cf. Yu & Rugg, 2010; Woodruff et al., 2006; Yonelinas et al., 2005). For the remember, confident old, and confident new categories, mean trial numbers (range, in parentheses) after preprocessing to eliminate trials contaminated by artifact were 40 (16–70), 41 (22–68), and 44 (30–70), respectively, for the young group and 28 (18–50), 49 (18–82), and 51 (17–101), respectively, for the older group.

Initial ANOVAs were conducted on data from both age groups across 12 electrodes, arranged in chains of three electrodes over each scalp quadrant (left anterior, right anterior, left posterior, and right posterior; see Figure 1). Each electrode chain extended from an inferior to a superior site. ERPs were conducted separately for the two latency regions described above. Results from the initial ANOVAs are reported in Tables 3 and 4 for all effects involving the factor of Response Category and its interaction with the factors of Age, Hemisphere, Anterior–Posterior Location, or Electrode Site. Subsidiary ANOVAs, reported below, were performed to elucidate the interactions revealed by the initial ANOVAs.

Familiarity-related ERP Effects

The initial ANOVA conducted on the 300–500 msec data associated with confident old and confident new responses revealed a main effect of Response Category and a significant

Table 3. Outcome of Initial ANOVA for Mean Amplitudes of ERPs Associated with Confident Old and Confident New Responses over the 300–500 msec Latency Region

<table>
<thead>
<tr>
<th>Effect</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rc</td>
<td>1, 42</td>
<td>17.90</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Group × Rc</td>
<td>1, 42</td>
<td>10.64</td>
<td>&lt;.005</td>
</tr>
<tr>
<td>Rc × Fp</td>
<td>1, 42</td>
<td>7.76</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Rc × Hm × Fp</td>
<td>1, 42</td>
<td>4.56</td>
<td>&lt;.05</td>
</tr>
</tbody>
</table>

Only effects that involve the factor of response category are reported. Rc = Response category; Hm = Hemisphere; Fp = Frontal–parietal.

Further ANOVAs on the data from each age group separately revealed a main effect of Response Category for the young group (F(1, 22) = 40.56, p < .001), but not for the old group (F < 1).

The foregoing analysis of the 300–500 msec latency region indicates the presence of a midfrontal effect in the young group only. It is possible, however, that the failure to find the effect in the older group merely reflects an age-related delay in its onset. To assess this possibility, we performed ANOVAs on the older participants’ frontal ERPs in two additional latency regions, 400–600 and 500–700 msec. In each case, the ANOVA gave rise to an interaction between Response Category and Hemisphere (400–600 msec: F(1, 20) = 7.57, p < .05; 500–700 msec, F(1, 20) = 17.34, p < .001). These interactions reflect a crossover effect between the two hemispheres, such that the waveforms elicited by confident old items are somewhat more negative than those for confident new items at left frontal sites but are more positive at sites over the right hemisphere. Effects of Response Category in follow-up ANOVAs on the data for each hemisphere were, however, uniformly nonsignificant [maximum F(1, 20) = 2.71, p > .1]. Thus, the findings from these later time regions offer little or no support for the possibility of a delayed midfrontal old–new effect in the older group.

In addition to the foregoing analysis of the midfrontal effect, we also contrasted the effect in balanced subsets of participants from each age group for whom familiarity strength was matched. We matched for familiarity by taking the maximum number of participants (15) in whom it was possible to statistically equate the mean accuracy of confident old responses (young: mean = 0.88, older: mean = 0.85; p > .1). Accuracy of confident new judgments

Table 4. Outcome of Initial ANOVA for Mean Amplitudes of ERPs Associated with Confident Old and Recollected Responses over 500–800 msec

<table>
<thead>
<tr>
<th>Effect</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rc</td>
<td>1, 42</td>
<td>108.42</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Group × Rc</td>
<td>1, 42</td>
<td>8.01</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Rc × Fp</td>
<td>1, 42</td>
<td>4.56</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Rc × Hm</td>
<td>1, 42</td>
<td>4.54</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Rc × Site</td>
<td>1.1, 45.0</td>
<td>39.78</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Group × Rc × Hm</td>
<td>1, 42</td>
<td>11.73</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Group × Rc × Site</td>
<td>1.1, 45.0</td>
<td>4.25</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Group × Rc × Hm × Site</td>
<td>1.4, 57.1</td>
<td>5.74</td>
<td>&lt;.05</td>
</tr>
</tbody>
</table>

Only effects that involve the factor of response category are reported. Rc = Response category; Hm = Hemisphere; Fp = Frontal–parietal.
(young: mean = 0.92, older: mean = 0.89; p > .1) and overall familiarity estimates (young: mean = 0.59, older: mean = 0.52; p > .1) were also equated. Recollection estimates remained higher for the young subgroup (0.34 vs. 0.22, t(28) = 3.72, p < .01), however.

The left and right frontal waveforms elicited by items endorsed as confident old and confident new are shown for the accuracy-matched older and young participants in Figure 3. As can be seen in Figure 3, whereas old–new effects are evident in the latency interval of 300–500 msec at both left and right frontal sites in the young participants, no such effects can be discerned in the older group. Although an ANOVA on the 300–500 msec data for the six frontal electrode sites across both age groups did not yield a reliable Response Category × Age Group interaction in these smaller samples, within-group analyses of these same electrode sites revealed a significant effect of Response Category for the young participants [F(1, 14) = 18.94, p < .005] but not for the older participants (F < 1). Thus, the finding of an undetectable midfrontal effect in the full sample of older participants cannot be attributed to these participants’ reliance on a familiarity signal weaker than the signal available to young participants.

In a final analysis conducted on the data from the young participants only, we determined whether the magnitude of the midfrontal old–new effect varied monotonically with familiarity strength, as we have reported previously (Yu & Rugg, 2010; Woodruff et al., 2006). As can be seen from Figure 4, this was the case. As in the prior studies, we assessed whether this monotonic trend was reliable by regressing the amplitude of the ERPs in the latency region of 300–500 msec at each frontal electrode against a dummy variable that coded for familiarity strength. Collapsed over the six frontal sites, the regression coefficient significantly differed from zero (mean = 0.39; t(22) = 6.05, p < .001), replicating our prior findings.

**Recollection-related ERP Effects**

An initial ANOVA on ERPs associated with recollected and confident old responses within the 500–800 msec latency region across all 12 electrode sites revealed a main effect...
of condition, along with Condition × Hemisphere and Condition × Age Group × Hemisphere interactions (see Table 4).

To directly compare recollection-related effects across age groups, a follow-up ANOVA on data from the six parietal electrode sites was performed. The ANOVA revealed a significant main effect of Response Category \[F(1, 42) = 120.72, p < .001\] and an Age Group × Response Category interaction \[F(1, 42) = 9.50, p < .005\]. The ANOVA also revealed an Age Group × Response Category × Hemisphere interaction \[F(1, 42) = 5.81, p < .05\], which was driven by a significant Age Group × Response Category interaction over the left sites \[F(1, 42) = 17.64, p < .001\] but not at the right parietal sites \[F(1, 42) = 2.73, p > .1\]. These results indicate that the magnitude of the parietal effect was smaller in the older participant group than in the younger participant group at left parietal sites only.

Additionally, ERPs associated with confident old responses were compared with those elicited by items given confident new responses. An ANOVA (factors of Age Group, Response Category, Hemisphere, and Site) was conducted on the data from the six parietal electrode sites. The ANOVA revealed an interaction between Response Category and Hemisphere \[F(1, 42) = 11.40, p < .005\], but no interaction with Age Group \(F < 1\). Follow-up ANOVAs revealed a significant Response Category effect for left hemisphere electrodes \[F(1, 42) = 7.86, p < .01\] but not for right hemisphere electrodes. Thus, this analysis indicates that the small left parietal difference between confident old and confident new items evident in Figures 1 and 2 is reliable, possibly indicating that some items endorsed as confident old carried a small recollection signal (cf. Wixted & Mickes, 2010). Importantly, there was no evidence that this effect differed according to age group. The equivalent analysis conducted on the data from the familiarity-matched subgroups (see above) revealed the same pattern of effects \[Response Condition × Hemisphere interaction, F(1, 28) = 8.91, p < .01; Response Condition × Hemisphere × Age Group interaction, F < 1\].

To assess whether the between-group differences in the magnitude of the left parietal effect reflected the lower recollection estimates in the older group (see Behavioral Performance above), we used a matching procedure analogous to that employed for familiarity strength to form two balanced subgroups \((n = 16, in each group)\), in which recollection was statistically equated \(p_{\text{Recollection}} = 0.28\) and 0.25 for young and older subgroups, respectively; \(p > .1\). familiarity estimates remained higher in the young subgroup, however: 0.63 vs. 0.49; \(t(30) = 3.25, p < .005\). The corresponding grand-averaged waveforms are illustrated in Figure 5, where it can be seen that the left parietal effect appears to be still smaller in the older participants. This impression was confirmed by ANOVA of the 500–800 msec latency data from the three left parietal electrode sites, which gave rise to an Age Group × Response Category interaction \[F(1, 30) = 14.67, p < .005\].

**Analysis of Scalp Topographies**

The scalp topographies of the familiarity-related old–new effects in the 300–500 msec latency region (young participants only) and the recollection-related effects in the 500–800 msec region (young and older participants) are illustrated in Figure 6A and B. Statistical analyses of the topographies of the effects were performed on the same subtraction data illustrated in the figures after range normalization (rescaling) to eliminate the confounding effects of global differences in the magnitude of the effects (McCarthy & Wood, 1985). The ANOVA contrasting the topographies of the early and later effects identified in the young participants revealed a significant Latency Region × Site interaction \[F(4, 95.1) = 4.9, p < .005\], indicating that these two topographies were significantly different (see Yu & Rugg, 2010; Woodruff et al., 2006, for similar findings). A second ANOVA contrasting the topography of the recollection-related effects in the 500–800 msec Latency Region according to Age Group revealed a significant effect of Site \[F(3.7, 157.0) = 5.80, p < .001\], but no significant interaction with Age Group \[F(3.7, 157.0) = 1.34, p > .1\].

**DISCUSSION**

The primary aim of the present study was to compare the electrophysiological correlates of familiarity-driven
recognition memory in older and young participants. In contrast to the young group, we failed to find evidence for a midfrontal familiarity-related effect in the older sample. Below, we discuss the implications of these findings.

Behavioral Performance

Both recollection and familiarity estimates were lower in the older participant group. The findings for recollection are consistent with those of numerous prior studies and add to the general consensus that recollection is highly vulnerable to advancing age. Although they conflict with some prior reports, the findings for familiarity are consistent with other evidence that, like recollection, familiarity can also be vulnerable to increasing age (see Introduction). The reasons for these disparate findings are currently unclear but are not obviously accounted for by differences in test procedure. For example, whether familiarity has been estimated using remember–know, source memory (process dissociation) or receiver operating characteristic procedures, both null (e.g., Howard et al., 2006; Jennings & Jacoby, 1997; Perfect et al., 1995) and significant (e.g., Parks, 2007; Prull et al., 2006; Toth & Parks, 2006) effects of age have been reported. As we discuss below, one possibility is that the extent to which familiarity-driven recognition is impaired in older participants relative to younger participants is determined by whether older participants have access to or make use of the same sources of familiarity information that are available to young individuals.

ERP Findings

Familiarity-related Effects

The failure to detect a midfrontal old–new effect in our older participant group replicates the findings of Duarte et al. (2006; see Introduction) and Trott et al. (1999). Unlike in those prior studies, the test procedure employed in the current study minimized (although it did not eliminate) the confounding effects of age-related differences in familiarity strength on the ERP measures. Crucially, the pattern of findings for the midfrontal effect was unaltered when the analysis was repeated in older and young subgroups, in whom familiarity strength (operationalized by accuracy of confident old and confident new judgments; Wixted et al., 2010) was closely matched. Together, these findings indicate that the failure to detect a midfrontal old–new effect in older participants cannot solely be attributed to their reliance on a familiarity signal that is weaker than the signal available to young participants.

Before continuing, it is important to note that our failure to detect a midfrontal effect in our older participant group does not necessarily mean that the neural populations reflected by the effect were insensitive to differences in the familiarity strength of the test items—such an assertion would amount to affirming a null effect. Thus, we leave open the possibility that a study with more statistical power or that employed more sensitive ERP analysis methods might have detected a reliable effect in the older participants. This caveat does not, however, detract from the conclusion that, if present at all, the midfrontal old–new effect in our older group demonstrated a dramatic reduction in its sensitivity to the relative familiarity of recognition test items.

The implications of our findings for elucidating the effects of age on familiarity-driven recognition memory depend on the functional significance of the midfrontal old–new effect. Whereas there is strong evidence that the effect is a neural correlate of familiarity strength in many circumstances (see Rugg & Curran, 2007, for a review; see Yu & Rugg, 2010; Stenberg, Hellman, Johansson, & Rosén, 2009, for relevant subsequent studies), this does not mean that it is a direct reflection of the neural processes that support the derivation and representation of item familiarity. Notably, Tsivilis, Otten, and Rugg (2001; see also Ecker, Zimmer, & Groh-Bordin, 2007) reported that the midfrontal effect was absent for studied test items presented in conjunction with novel as opposed to experimentally familiar background contexts, despite the fact that the familiarity of the items (as indexed by the remember–know procedure) did not
differ from items paired with familiar contexts (i.e., the stimulus conjunction that did elicit the midfrontal effect). Tsivilis et al. (2001; see also Rugg & Curran, 2007) proposed that the midfrontal effect reflects a process, such as detection of a novel element in a stimulus event, that, although usually correlated with item familiarity, operates “downstream” of the computation of familiarity and does not contribute to item recognition.

Thus, the present findings might signify an age-related change not in the neural bases of familiarity but in an as-yet-unidentified downstream, familiarity-dependent process. Evidence favoring this possibility comes from the finding that the midfrontal effect can be dissociated from familiarity strength even in young individuals (see above), along with the present finding that the effect could not be detected even in those older individuals in whom familiarity strength was equated with a younger participant group. Further investigation of this possibility will depend upon the development of a hypothesis about the function of this putative process, along with its experimental operationalization.

Alternatively, the present findings might be indicative of a qualitative difference between the age groups in the nature of the familiarity signals supporting their recognition judgments. By this argument, the midfrontal effect reflects only one of what might be a multiplicity of signals capable of supporting familiarity-based recognition. Either because of age-related neural degradation or, perhaps, a shift in processing strategy, older individuals do not generate this signal (at least, not in the present study or those of Duarte et al., 2006, or Trott et al., 1999), relying instead on other sources of familiarity information that seemingly do not have a scalp ERP correlate. The finding that, in both the present study and Duarte et al. (2006), familiarity was weaker in older than in young participants offers support for this proposal if it is assumed that familiarity information not reflected by the midfrontal effect provides a less efficient basis for item discrimination.

It is not possible to adjudicate between the above two interpretations on the basis of the currently available evidence. There is, however, suggestive evidence that older participants are capable of generating a midfrontal old–new effect under some circumstances. Ally et al. (2008) contrasted the ERP old–new effects elicited by words and colored pictures in young and older participants. They reported that, whereas words failed to elicit a reliable midfrontal effect in their older group (see Wolk et al., 2009, for similar findings), a robust effect was evident for pictures (see also Eppinger, Herbert, & Kray, 2010). Because the retrieval test employed by Ally et al. (2008) merely required an old–new discrimination, it is not possible, however, to unequivocally associate the effect with a familiarity signal. If it does transpire that the familiarity-driven midfrontal effect can be “rescued” in older participants through the use of test materials such as colored pictures, it would then be less likely that when the effect is absent this can be attributed to age-related degradation of its neural generators. Why colored pictures might elicit a midfrontal effect in older participants when neither words (Wolk et al., 2009; Trott et al., 1999; the present study) nor grayscale pictures (Duarte et al., 2006) appear to do so is unclear. One possibility is that the effect becomes increasingly sensitive with age to the perceptual richness of the test items. Another, perhaps related, possibility is that colored pictures engender especially high levels of familiarity, overcoming the tendency of the effect to become less sensitive to differences in familiarity strength with age. Adjudicating between these and other possibilities would be a worthwhile focus for future research.

It is important to note that the interpretation of the midfrontal effect as a neural correlate of familiarity has not gone unchallenged. An alternative perspective (Voss, Schendan, & Paller, 2010; Voss, Lucas, & Paller, 2009; Paller, Voss, & Boehm, 2007; Voss & Paller, 2006, 2007) views the effect as a correlate of conceptual priming, arguing that the apparent association between the effect and familiarity strength occurs only when familiarity and priming are confounded (but see Stenberg, Hellman, Johansson, & Rosén, 2010; Yu & Rugg, 2010; Stenberg et al., 2009). Because conceptual priming is unaffected by normal aging (see Fleischman, 2007, for a review; see Bergerbest et al., 2009; Fleischman, Bienias, & Bennett, 2009, for examples of more recent studies), the present findings are no easier to interpret from this perspective than they are under the assumption that the midfrontal effect reflects familiarity strength. Thus, even more so than for the alternate proposal (as discussed above, familiarity is by no means invariably age-insensitive), the proposal that the midfrontal effect reflects conceptual priming must confront the finding that the effect is absent in a participant group (older adults) in whom its putative cognitive correlate is intact.

**Recollection-related Effects**

As reported in several prior studies (e.g., Duverne, Motamediāna, & Rugg, 2009; Duarte et al., 2006; Wegesin et al., 2002; Trott et al., 1999; Mark & Rugg, 1998), older participants demonstrated a robust, recollection-selective, parietal old–new effect. Consistent with most of these reports, the scalp distribution of the effect did not differ reliably with age, although in the present case, the effect was somewhat smaller in magnitude in the older participants (see also Trott et al., 1999). This difference in magnitude remained when recollection effects were contrasted between young and older subgroups equated for probability of recollection. The present findings are consistent with the proposal (e.g., Mark & Rugg, 1998) that advancing age impacts the probability of successful recollection, likely because of a decline in the effectiveness of both encoding and retrieval cue processing (Duverne et al., 2009; Morcom & Rugg, 2004), but that age has less influence on the processes engaged when a cue gives rise to successful recollection. Although the finding of a smaller recollection effect in older participants might be indicative
of some degree of age-related degradation in these processes, an alternative explanation is also possible. This stems from the finding that the magnitude of the parietal old–new effect covaries with the amount of episodic information recollected (Vilberg & Rugg, 2009; Vilberg, Moosavi, & Rugg, 2006). Thus, the present finding of an age-related reduction in the parietal old–new effect might reflect a tendency for recollection to have been accompanied by the retrieval of less information in older than in young participants. Whether this tendency (should it exist) is a consequence of age differences in the amount of information initially encoded or whether it reflects differences in retrieval processing is an interesting question for the future.

Conclusions

Consistent with prior reports (Duarte et al., 2006; Trott et al., 1999), the present findings demonstrate that the putative ERP correlate of familiarity-driven recognition memory—the midfrontal old–new effect—is markedly attenuated in healthy older individuals. Furthermore, this age-related difference cannot be attributed to the confounding effect of a weaker familiarity signal in older than in younger participants. The functional significance of this striking age-related dissociation in the neural correlates of memory retrieval remains to be elucidated, but this does not detract from the conclusion that age exerts a profound influence on the processing of recognition memory test items.

Acknowledgments

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Notes

1. Perfect et al. (1995) reported reduced familiarity estimates in older participants in their Experiment 1.
2. Yu and Rugg (2010) demonstrated that the relationship between midfrontal effect and familiarity strength does not differ according to whether the effect is elicited by studied test items only or by items collapsed over study status. There were insufficient trials in the present study to replicate that analysis here, but we were able to contrast ERPs elicited by old and new items that had been equated for familiarity strength (see Woodruff et al., 2006) for 20 older participants and 22 young participants (one participant from each group did not have sufficient trials in one of the conditions). Effects of study status were nonsignificant in both age groups. Thus, as in Woodruff et al. (2006), the variable of familiarity strength was not confounded with the effects of study status.
3. A reviewer noted that these interactions represent a processing difference in older adults as a function of familiarity strength and might indicate the engagement of a familiarity-sensitive network in these individuals, albeit one qualitatively distinct from that indexed by the midfrontal old–new effect.
4. Eleven young participants and 12 older participants were also members of the familiarity-matched subgroups.
5. We also quantified the left parietal old–new effect using group-specific latency regions (young: 600–800 msec; older: 700–900 msec) so as to capture the maxima of the effects in each group, which peaked some 100 msec later in the older participants. The ANOVA of the data from the left parietal electrode sites again revealed a significant Age × Response Category interaction [F(1, 30) = 4.63, p < .05], suggesting that the finding of a smaller effect in the older participants is not because of the employment of a latency region favoring the young group.
6. Duarte et al. (2006) segregated their older participant sample on the basis of a median split in recognition performance. Whereas the parietal old–new effect was intact in the high-performing subgroup, it was markedly attenuated in the low-performing group.

REFERENCES


