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PAPER

Electrophysiological evidence for late maturation of strategic episodic retrieval processes

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Abstract

Improvement in source memory performance throughout development is thought to be mediated by strategic processes that facilitate the retrieval of task-relevant information. Using event-related potentials (ERPs), we examined developmental changes in these processes during adolescence. Adolescents (13–14 years) and adults (19–29 years) completed a memory exclusion task which required the discrimination between words studied in one color ('targets') and words studied in the alternative color ('non-targets') under two conditions that put different demands on strategic control. Memory accuracy improved with age and also increased with decreasing control demands in both age groups. The parietal old/new effect, an ERP correlate of recollection, was reliable for targets across conditions in both age groups. By contrast, ERP correlates of non-target recollection were present in adolescents across conditions but not in adults. This suggests that adults implemented a strategy to prioritize recollection of target information with greater success than adolescents regardless of control demands, presumably reflecting maturational differences in cognitive control. In support of this view, the ERP amplitude difference between targets and non-targets was positively correlated with a measure of working memory capacity (WMC) in adults but not in adolescents. A further age-related difference was that ERP correlates of post-retrieval processing, including late right-frontal old/new effects and late posterior negativities, were observed in adults only. Together, our data suggest protracted maturation in the strategic processes that underlie selective recollection and post-retrieval control.

Introduction

Cognitive development is supported by cognitive control processes that mature during adolescence (Best & Miller, 2010). Of interest here is the development of control processes that mediate episodic memory. These control processes are thought to be essential for source memory retrieval and to encompass operations that occur prior to and after the recovery of information, including the specification of the task-relevant contextual details to be retrieved and the monitoring of memory outputs against the specified retrieval criteria (e.g. Schacter, Norman & Koutstaal, 1998; Simons, 2009). The ensemble of operations at these stages of source retrieval will be henceforth referred to as *strategic retrieval processing*.

Support for the role of cognitive control in memory retrieval comes from neuroimaging research which has implicated several regions within prefrontal cortex (PFC) in strategic retrieval (Simons & Spiers, 2003). This brain area has been shown to undergo protracted maturation, with critical structural changes occurring until late adolescence in the form of synaptic pruning and myelination (O'Hare & Sowell, 2008). In line with this are data on functional brain development, which indicate that the networks that underlie cognitive control, including inhibition and working memory, specialize and refine throughout adolescence (Luna, Padmanabhan & O'Hearn, 2010). As such, one might expect a similarly protracted developmental course in strategic memory retrieval.

Behavioral research has shown that memory strategies develop during childhood and adolescence as reflected by improvements in elaborative encoding (Shing, Werkle-Bergner, Li & Lindenberger, 2008) and organization in recall (Bjorklund & Jacobs, 1985; for reviews see Bjorklund & Douglas, 1997; Schneider & Pressley, 1997). Despite the wealth of behavioral data on memory strategy development, however, there is only little evidence about changes in the neural correlates of strategic retrieval processing available to date. The goal of this study, therefore, was to investigate these changes by means of ERPs.

A number of studies have used ERPs to identify neural correlates of distinct classes of episodic retrieval process involved in source memory (Friedman & Johnson, 2000; Mecklinger, 2000). Of particular interest here is the ERP correlate of recollection, the *parietal old/new effect*. This effect takes the form of a greater positivity for studied than unstudied items over parietal recording sites that onsets around 400 to 500 ms post-stimulus and often

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shows a left-sided maximum. The evidence linking the parietal old/new effect to recollection comes from a number of demonstrations that the effect is sensitive to common operational definitions of recollection (see Rugg & Curran, 2007, for a review). For example, the magnitude of the effect has been found to correlate with the amount of information recollected, which has generated suggestions that it can act as an index of the extent to which recollection has occurred (Vilberg, Moosavi & Rugg, 2006; Vilberg & Rugg, 2009; Wilding, 2000). A further ERP correlate of episodic retrieval is the mid-frontal old/new effect between 300 and 500 ms. Because this effect is sensitive to manipulations of familiarity, such as response speed (Mecklinger, Brunnemann & Kipp, 2011), it is considered to reflect familiarity-based remembering (Mecklinger, 2006).

Of additional importance here are two ERP modulations that have been associated with processes that act downstream of source recollection (i.e. post-retrieval processes). The right-frontal old/new effect often occurs in a post-response period and is taken to reflect processes that serve to monitor the products of retrieval in the service of task demands (Cruse & Wilding, 2009; Hayama, Johnson & Rugg, 2008). The late posterior negativity (LPN), showing similar temporal characteristics to the right-frontal effect, has been associated with the search for and/or evaluation of context-specifying information from a prior study episode (Johansson & Mecklinger, 2003).

The sensitivity of the parietal old/new effect to the amount of information recollected has been used to address several questions regarding the strategic control of episodic retrieval, with one example being the control of recollection in memory exclusion tasks (Jacoby, 1991). The exclusion task includes a study phase in which items are studied in one of two contexts, while during the test phase, participants respond ‘old’ to items belonging to one context (*targets*) and ‘new’ to items from the second context (*non-targets*) as well as to new items. Successful discriminations between targets and non-targets in this paradigm are assumed to depend on recollection, and one way in which the task can be completed is by recollecting contextual information associated with targets and non-targets (Jacoby, 1991). Support for this view comes from ERP studies that have reported reliable parietal old/new effects for targets and non-targets using source features such as color (Cycowicz, Friedman & Snodgrass, 2001a) or encoding operations (Dzulkifli, Herron & Wilding, 2006).

An alternative strategy for completing this task, however, is to attempt to recollect information associated with targets only and to use the success or failure of target recollection as the basis for accurate discriminations (Herron & Rugg, 2003b). The proposal of target-selective retrieval is in line with studies that have reported parietal ERP old/new effects for targets only, indicating that non-target recollection can be inhibited under certain conditions (e.g. Dzulkifli & Wilding, 2005). Critically, one factor that appears to influence the extent to which recollection of target information can be prioritized over non-target recollection is the ease of target discrimination. The evidence that underlies this account comes from a series of paradigms where reliable non-target old/new effects were observed in those conditions where target accuracy was relatively low (Fraser, Bridson & Wilding, 2007; Herron & Rugg, 2003b; Rosburg, Mecklinger & Johansson, 2011b; Wilding, Fraser & Herron, 2005). For example, Wilding *et al.* (2005) observed that across two experiments that differed in task difficulty, low target accuracy was associated with parietal old/new effects for targets and non-targets, while high accuracy was associated with target effects only. A preferred interpretation of these findings is that as target memories become insufficiently reliable to support selective retrieval, participants recollect information associated with targets and non-targets.

In addition to this interpretation, Elward and Wilding (2010) proposed that individual resources available for cognitive control will also influence the degree of engagement in target-selective recollection. Consistent with this proposal was their finding that the degree to which parietal ERP old/new effects elicited by targets were larger than non-target effects was correlated positively with WMC, suggesting that the extent to which recollection can be constrained depends upon cognitive resources. This in turn allows for the possibility that the processes that underlie selective retrieval develop along with other cognitive control functions during maturation. In the following, we briefly review previous ERP findings on strategic retrieval processing in younger age groups and then outline the rationale of our study.

To date, the issue of developmental change in selective retrieval has not yet been addressed; however, several ERP studies have examined age differences in non-target recollection to support task performance (Czernochowski, Mecklinger & Johansson, 2009; Czernochowski, Mecklinger, Johansson & Brinkmann, 2005; Sprondel, Kipp & Mecklinger, 2011). For example, Czernochowski *et al.* (2005) examined memory for the study modality (photos vs. spoken words) with line drawings as retrieval cues in 6–12-year-old children and adults. While all age groups showed reliable parietal old/new effects for targets, only adults showed a non-target retrieval effect. This latter effect was even larger when studied photos served as non-targets which due to their high perceptual similarity with the test cues could more easily be retrieved than targets. This is consistent with the view that in cases of high compatibility between cues and non-targets adults recollect non-targets along with targets (Herron & Rugg, 2003a). Notably, this non-target retrieval effect was absent in children, suggesting that this kind of strategic retrieval processing is still immature in late childhood.

Conversely, in a recent study, non-target retrieval was found to emerge with adolescence, as evidenced by a non-target ERP old/new effect in 14-year-old adolescents, coupled with adult-like source discrimination abilities (Sprondel *et al.*, 2011). However, in contrast to adolescents, in the adult group this effect was followed by a right-frontal effect. This was taken to indicate that the neural network underlying strategic retrieval is available for young adolescents but still lacks the refinement to support post-retrieval monitoring. The latter view receives additional support from a study which reported electrophysiological correlates of response inhibition for non-targets and of post-retrieval monitoring for targets in the response-locked ERP of young adults but not in that of 13-year-old adolescents (de Chastelaine, Friedman & Cycowicz, 2007). This confirms the view that post-retrieval control processes mature during adolescence.

Taken together, these ERP findings suggest that adolescence is a crucial phase for the maturation of controlled memory retrieval. However, because these changes have been predominantly revealed at the post-retrieval processing stage of strategic retrieval, the important question remains as to whether maturation also affects strategic recollection, as measured by target and non-target ERP old/new effects. Therefore, the purpose of this study was to investigate developmental changes in the ability to prioritize recollection of targets over non-targets in a memory exclusion task.

The sensitivity of target-selective retrieval processing to individual differences in cognitive control (Elward & Wilding, 2010), as well as the protracted maturation of cognitive control (Luna *et al.*, 2010), allows for the prediction that young adolescents show generally fewer abilities to implement selective retrieval strategies compared to adults. A related proposal is that the degree to which adolescents engage in strategic retrieval processing depends upon task-specific demands on strategic control, given that target-selective retrieval is facilitated by high target discriminability (Herron & Rugg, 2003b). The present study was designed to test both of these possibilities by determining the effects of task difficulty on age differences in strategic retrieval processing. Two difficulty conditions were created, both of which required that target/non-target judgments were made for words according to their study color. In order to ensure that memory accuracy would reliably differ across conditions, task difficulty was manipulated by simultaneously varying two independent task parameters. In the easy condition, therefore, shorter study and tests lists and a smaller degree of similarity between study colors compared to the difficult condition were used.

We expected this manipulation to result in a higher likelihood of discriminating targets from non-targets in the easy compared to the difficult condition for both age groups. We also predicted that adults would perform more accurately in target/non-target discrimination than adolescents. Regarding the neural correlates of this developmental difference, the following predictions were made. For adults, parietal ERP old/new effects for targets were expected for both conditions, while non-target effects, if they occur, should be restricted to the difficult condition. By contrast, adolescents were expected to show parietal old/new effects for targets and non-targets in both difficulty conditions, supporting the view that the neural network underlying target-selective recollection is generally immature at that age. However, it is also conceivable that adolescents show evidence of non-target recollection in the difficult but not in the easy condition, indicting that the network is mature enough to support tasks with high target discriminability. In keeping with the outcomes of previous investigations (de Chastelaine *et al.*, 2007; Sprondel *et al.*, 2011), we also predicted developmental changes in the ERP correlates of post-retrieval processing. Thus, right-frontal old/new effects as well as LPNs were expected to occur in adults, while in adolescents these effects should be absent or less consistently present.

In order to further explore the development of strategic recollection, we determined in both age groups the relationships between an estimate of WMC and the ERP amplitude difference between targets and non-targets. Under the assumption that this ERP measure indexes the degree to which target-selective retrieval processing is engaged (Elward & Wilding, 2010), we considered it informative whether it would be differentially related to WMC in adolescents and adults. While we expected the ERP target/non-target difference amplitude to correlate positively with WMC in both difficulty conditions for adults, an interesting issue is whether this kind of relationship would also be observed for adolescents.

Method

Participants

Twenty-six adolescents and 24 young adults participated in the study. The data of eight adolescents and four adults were discarded due to insufficient trials in at least one response category, resulting from a combination of low performance levels and excessive movement artifacts. Of the participants included in the analysis, adolescents were 13–14 years old ($M = 13.44$, $SD = 0.51$; 8 male), and adults were 19–29 years old ($M = 24.10$, $SD = 2.80$; 11 male). All participants were native German speakers, right-handed, had normal or corrected-to-normal vision, and reported not suffering from color blindness. Adolescents were recruited from the immediate vicinity. Adults were undergraduate students from Saarland University. Participants (and adolescents' parents) gave informed consent and received €8/hour for participation.

Materials

Exclusion task

The stimuli comprised high-frequency words (CELEX psycholinguistic database: > 7/million) denoting concrete objects. Words ranged between three and ten letters in length; 180 words were used in the difficult condition and 150 words were used in the easy condition. Words were presented in colored letters in the study phases and white letters in the test phases on a black background at the center of a monitor 1 m from participants.

WMC measurement

WMC was measured by means of an operation span task (Turner & Engle, 1989). Stimuli consisted of 42 arithmetic operations, followed by a word, such as 'Is (8/2) – 2 = 1? Wire'. Participants were asked to read the equation aloud, to indicate whether the solution was correct, and then to read the word aloud while remembering it for a later recall test. The 42 operation–word pairs were divided into 12 items so that each item consisted of either two, three, four or five pairs, presented in random order. Each test required recall of all words presented in each item. We used partial-credit load scoring by which one point is awarded for every correctly recalled word (Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005).

Design

The manipulation of task difficulty was blocked in the experiment, so that the difficult and the easy conditions were completed in two successive blocks. The order of these blocks was counterbalanced across participants. In the difficult condition, the 180 words were equally distributed between six study-test cycles, each containing 20 study words (10 target and 10 non-target words) and 30 test words (20 old and 10 new words). In the easy condition, the 150 words were equally distributed between 10 study-test cycles, each containing 10 study words (5 target and 5 non-target words) and 15 test words (10 old and 5 new words). In both conditions, the words were rotated so that, across participants, each word served equally often as target, non-target, and new word. Thus, three different task-lists were created for both conditions which were completed by an equal number of participants. The order of word presentation in all study and test phases was determined randomly for each task-list.

The colors in which the words were presented during the study phases were set at a level that ensured that the perceptual target/non-target distinctiveness was lower in the difficult compared to the easy condition. Therefore, words in the difficult condition were presented in either pink (RGB: 255-0-120) or red (RGB: 255-0-0), and words in the easy condition were presented in either pink (RGB: 255-0-120) or green (RGB: 0-176-80). In both conditions, the color for designating target words was the same in half of the study-test cycles (three in the difficult and five in the easy condition). To control for the number of times in which response requirements changed from one study-test cycle to the subsequent cycle, two fixed sequences of target color were created for both conditions (Difficult: red-pink-pink-red-red-pink and pink-red-red-pink-pink-red; Easy: green-green-green-pink-pink-pink-green-green-pink-pink and pink-pink-pink-green-green-green-pink-pink-green-green). These sequences were counterbalanced across participants.

Procedure

Participants were fitted with an electrode cap before the experiment. A practice phase with 15 additional words was used to familiarize participants with the task instructions. They were informed that there were several study-test cycles in which they would have to remember the color of previously learned words. They were also informed that target color would only be revealed at the start of each test phase and might change across cycles. Participants were not informed, however, about the sequences of target color and the number of study-test cycles in each condition.

In each study phase, participants in both age groups performed an encoding task that was similar to previous investigations of source memory with young adults (Diana, Yonelinas & Ranganath, 2008; Staresina & Davachi, 2006): participants were asked to vividly image each object in the same color in which the denoting word was presented and to rate via key press whether or not the object was plausible in this color. A 4-point scale was used for this judgment: 1 = 'very realistic', 4 = 'very unrealistic'.[1] In each test phase, participants were required to respond with one hand to words previously presented in the target color (targets) and to respond with the other hand to words presented in the other color (non-targets) as well as to new words. Responses were made on a response box with the left and right index fingers. Response hands were counterbalanced across participants. Participants were encouraged to balance speed and accuracy of their responses equally.

Study trials began with a fixation cross (300 ms), followed by a blank screen (200 ms) after which the study word was presented (600 ms). The screen was then blanked for 2300 ms during which participants made the plausibility judgment. There was an interval of approximately 1 min between each study and test phase, during which participants performed a counting task (40 sec) and were informed about the target color for the test phase (10 sec).

Test trials also began with a fixation cross (300 ms), followed by a 200 ms baseline blank screen period. Test words were presented for 400 ms after which the screen was blanked. Responses were recorded within 2000 ms

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[1] In order to investigate whether the age groups differed in the way or in the efficiency with which study words were encoded, we investigated whether adolescents differed from adults in the distribution of study responses across the four response options and in RTs of study responses. None of these analyses revealed evidence of reliable age differences in these measures, suggesting that the processing of the encoding task was highly similar across age groups.

after stimulus onset, and the next trial began 1000 ms after the response.

After the experiment, participants completed a color discrimination task in which the color of a stimulus (XXXXX) presented on a black background had to be indicated via a key press. There were two successive blocks, requiring either pink/red or pink/green judgments. The RGB codes used for these colors were the same as in the memory task, as was the way in which the order of the blocks was counterbalanced across participants. Each block contained 40 trials, half of which were presented in one color and the remainder in the alternate color. Trials began with the stimulus (400 ms), followed by a 1100 ms blank screen period during which participants made the response. After another 400 ms, the following trial began. Task instructions emphasized speed and accuracy equally. Finally, the Operation Span task was administered to participants. The whole session lasted for approximately two hours.

Electroencephalogram (EEG) recording

EEG was recorded from 27 Ag/AgCl- electrodes located at the following sites (adapted from the standard 10–20 system): FP1, FP2, F7, F3, FZ, F4, F8, FC5, FC3, FCZ, FC4, FC6, T7, C3, CZ, C4, T8, CP3, CPZ, CP4, P7, P3, PZ, P4, P8, O1, O2. Electrode impedance was kept below 5 kΩ. EEG was acquired continuously at 500 Hz with the left mastoid as the reference electrode, and was re-referenced offline to the average of both mastoids. Electro-ocular activity (EOG) was recorded from above and below the right eye and from the outer canthi of both eyes. EOG artifacts were corrected using a linear regression estimate (Gratton, Coles & Donchin, 1983), whereas trials containing muscular and/or technical artifacts were rejected. The epoch length was 1400 ms, including a 200 ms prestimulus baseline relative to which all mean amplitudes were computed.

Averaged ERPs were formed for correct judgments at test to target, non-target, and new words for each participant in each condition. In both conditions, the ERPs were collapsed across target color. For adults, the mean trial numbers (range) for target, non-target, and new words were: difficult, 36 (19–52), 36 (20–50), 50 (39–58); easy, 35 (26–47), 32 (19–45), 43 (36–50). The equivalent values for adolescents were: difficult, 28 (16–49), 26 (16–46), 40 (21–56); easy, 28 (16–44), 27 (16–42), 37 (18–48).

Data analyses

All trials in which no response was given were discarded from behavioral analysis. Behavioral and ERP data were analyzed using ANOVAs for repeated measures including the factors Age (adults, adolescents), Difficulty (difficult, easy), and, except for the analyses of memory accuracy and response bias, the factor Item Type (IT; target, non-target, new). Effects that did not involve the IT factor are not reported. All analyses included Greenhouse-Geisser corrections for nonsphericity, and where necessary corrected p-values are reported (Greenhouse & Geisser, 1959).

Results

Behavioral data

The mean values of Operation Span scores were 27.75 ($SD = 7.28$) for adults and 25.22 ($SD = 6.25$) for adolescents. A one-way ANOVA revealed no age differences in these scores ($p = .26$).

The probabilities of correct color discrimination judgments were statistically equivalent between the pink/red and the pink/green blocks for both adolescents (pink/red: $M = .95$, $SD = .04$; pink/green: $M = .96$, $SD = .04$) and adults (pink/red: $M = .96$, $SD = .04$; pink/green: $M = .98$, $SD = .03$), as assessed by separate ANOVAs for both age groups (p-values $> .11$). These analyses were conducted to ensure that effects of the difficulty manipulation on behavioral and ERP data can be attributed to the ease of memory retrieval rather than to differences in perceptual discriminability. Therefore, the pattern obtained here suggests that these difficulty effects are unlikely to reflect differences in color discrimination.

Table 1 shows probabilities and reaction times (RTs) of correct responses to targets, non-targets, and new words in the difficult and easy conditions for both age groups. Memory accuracy was defined as the discrimination index Pr (Snodgrass & Corwin, 1988). Of critical importance here is the index of source discrimination (Pr_Source), which, consistent with previous approaches (e.g. Bridger, Herron, Elward & Wilding, 2009), was defined with regard to the discrimination between targets and non-targets [Pr_Source = p(target hit) − p(non-target false alarm)]. A target/new discrimination index was

Table 1 *Memory performance data for both age groups in both conditions*

	Adults		Adolescents	
	Difficult	Easy	Difficult	Easy
p(correct)				
Targets	.81 (.11)	.87 (.09)	.73 (.12)	.81 (.11)
Non-Targets	.76 (.12)	.81 (.14)	.67 (.13)	.75 (.12)
New	.96 (.04)	.98 (.02)	.96 (.03)	.97 (.03)
Pr_Source	.57 (.19)	.68 (.19)	.40 (.18)	.57 (.21)
Pr_New	.77 (.13)	.84 (.10)	.69 (.12)	.79 (.12)
Br	.17 (.09)	.16 (.08)	.15 (.17)	.14 (.13)
RT (ms)				
Targets	906 (141)	860 (161)	937 (152)	889 (136)
Non-Targets	937 (145)	939 (200)	941 (170)	933 (117)
New	748 (107)	716 (109)	797 (158)	756 (118)

Note: Memory accuracy was calculated with regard to non-targets [Pr_Source = p(target hits) − p(non-target false alarms)] and new items [Pr_New = p(target hits) − p(new item false alarms)]. Response bias was calculated with regard to new items [Br = p(new item false alarms)] / (1 − Pr_New)]. Reaction times are given for correct responses to new, old, non-target, and target items. Standard deviations of means are given in parentheses.

also calculated, defined as Pr_New = p(target hit) − p(new item false alarm). This index was then used to compute response bias, defined as Br = p(new item false alarm) / 1 – Pr_New (Snodgrass & Corwin, 1988).

To analyze age differences in memory accuracy and response bias, Pr_Source, Pr_New, and Br were subjected to separate ANOVAs with the factors Age and Difficulty. The analyses of memory accuracy revealed that adults performed better than adolescents, as reflected in main effects of age for Pr_Source [$F(1, 36) = 6.54$, $p < .05$] and Pr_New [$F(1, 36) = 4.08$, $p = .05$]. Main effects of Difficulty [$F(1, 36) = 25.00$, $p < .001$ and $F(1, 36) = 17.52$, $p < .001$ for Pr_Source and Pr_New, respectively], indicated that, across age groups, memory accuracy was higher in the easy than in the difficult condition. The analysis of response bias revealed no significant effects (p-values > .65).

For the RT data, an ANOVA with the factors Age, Difficulty, and IT revealed main effects of IT [$F(2, 72) = 100.43$, $p < .001$] and Difficulty [$F(1, 36) = 8.33$, $p < .01$] as well as an interaction between these two factors [$F(2, 72) = 6.05$, $p < .01$]. Follow-up analyses revealed that new words yielded faster responses than targets and non-targets in both conditions (p-values < .001). Target responses were faster than non-target responses in the easy ($p < .001$) but not in the difficult condition ($p = .12$). Compared to the difficult condition, the easy condition yielded faster responses to targets and new words (p-values < .001) but not to non-targets ($p = .86$).

To summarize, consistent with our expectation, the likelihood of discriminating targets from non-targets and new words increased with decreasing task difficulty for both age groups and also improved with age in both difficulty conditions. No such differences were evident for response bias. In terms of RTs, there were no age differences in the processing of targets, non-targets, and new items. Both age groups responded faster in the easy than in the difficult condition to targets and new words but not to non-targets.

ERP data

Figure 1 shows the ERPs from nine selected recording sites in the difficult and the easy conditions for the adolescents and the adults. The figure shows the ERPs elicited by correct judgments to target, non-target, and new words. Between 300 and 500 ms, both age groups showed more positive waveforms for old (targets and non-targets) relative to new words at frontal sites in both conditions. From 500 to 700 ms, adults showed more positive-going ERPs for targets relative to non-targets and new words at parietal sites. An additional positivity for non-targets was seen at frontal sites between 500 and 700 ms in the difficult condition for adults. In adolescents, parietal positivities were present for both targets and non-targets between 500 and 700 ms. From 900 to 1200 ms, adults showed right-frontal old/new effects for targets, accompanied by greater negativities (LPN) for old relative to new words at parietal locations. Figure 2 shows the scalp distributions of the ERP old/new effects for targets and for non-targets in both conditions over three time-windows: 300–500 ms and 500–700 ms to capture the early frontal and the parietal old/new effects, in addition to the 900–1200 ms interval, to capture the late posterior negativities and right-frontal effects.

Age differences in ERP correlates of familiarity, recollection, and post-retrieval processes

These were assessed in a series of analyses of mean amplitudes of ERPs to targets, non-targets, and new items, collected from the nine electrodes shown in Figure 1 (F3, FZ, F4, C3, CZ, C4, P3, PZ, P4). These electrodes largely correspond to the locations that were previously employed to contrast ERP correlates of strategic retrieval across age groups or difficulty conditions (Czernochowski *et al.*, 2005; Wilding *et al.*, 2005), and were selected after visual inspection of the principal ERP divergences between the age groups. The electrodes were grouped into anterior/posterior (AP: frontal, central, parietal) and Laterality (left, midline, right) factors in all analyses. In keeping with previous approaches (see Rugg & Curran, 2007, for a review), the early frontal and the parietal old/new effects were evaluated from 300 to 500 ms, and from 500 to 700 ms, for both age groups. To evaluate the right-frontal old/new effects and LPNs for adults, visual inspection of the ERPs suggested using a time-window from 900 to 1200 ms for these analyses.

For each of the 300–500, 500–700, and 900–1200 ms time-windows, an initial analysis incorporated data from both age groups (Age) and conditions (Difficulty), in addition to the factors of IT, AP, and Laterality. Each of these analyses revealed interactions between Age and IT [300–500 ms: $F(2, 72) = 5.38$, $p < .01$; 500–700 ms: $F(2, 72) = 6.36$, $p < .01$; 900–1200 ms: $F(2, 72) = 3.25$, $p < .05$]. The age-specific profiles of ERP effects were then established by separate analyses for each time-window and age group. These analyses included the factors of Difficulty, IT, AP, and Laterality and were followed up with subsidiary paired contrasts of the ERPs to targets, non-targets and new items. An overview of the outcomes of these contrasts is provided in Tables 2 and 3 for adults and adolescents, respectively. The following description of the age-specific analyses is restricted to the highest-order interactions that were obtained in each case.

300–500 ms

For adults, the initial ANOVA revealed a four-way interaction between Difficulty, IT, AP, and Laterality [$F(8, 152) = 2.28$, $p < .05$]. Follow-up contrasts revealed robust old/new effects for targets and non-targets across locations in both conditions. In the easy condition, the target old/new effect exhibited a maximum at CZ. The target/non-target contrast revealed a widespread target

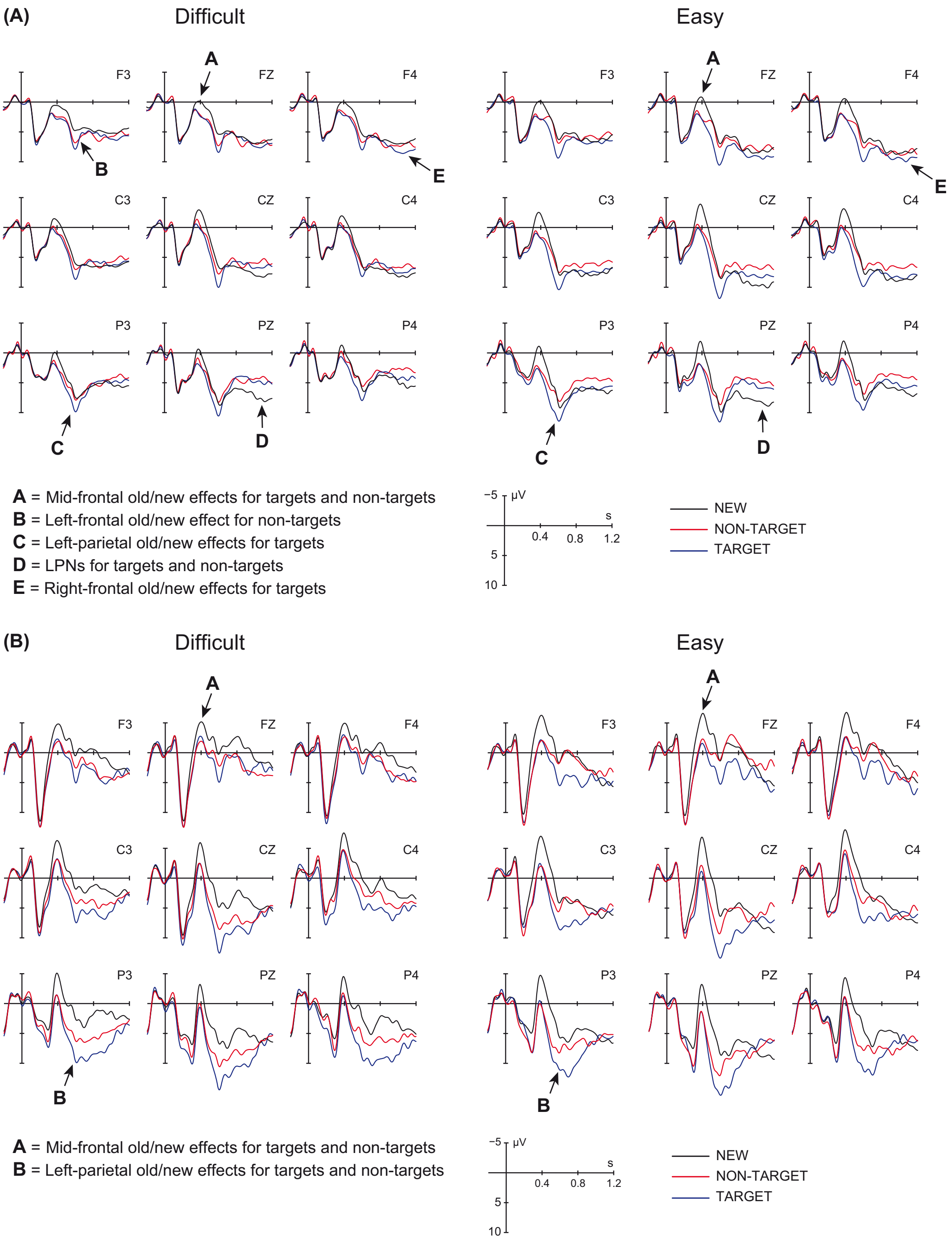

Figure 1 *Grand average ERPs elicited by correct judgments to targets, non-targets, and new words for adults (A) and adolescents (B) in both difficulty conditions. The ERPs are shown at nine electrodes (frontal: F3, Fz, F4; central: C3, Cz, C4; parietal: P3, Pz, P4). Arrows indicate the ERP effects identified in both age groups, and the letters (A–E in A; A–B in B) indicate the type of ERP effect along the time axis of processing.*

positivity in the easy condition, while no significant differences were obtained in the difficult condition.

For adolescents, the initial ANOVA revealed no interactions involving Difficulty and IT (*p*-values > .19). Therefore, follow-up contrasts were collapsed across both conditions. As indicated by the IT by Laterality interactions, old/new effects for targets and non-targets were larger across the midline compared to left and right hemisphere locations.

500–700 ms

For adults, a Difficulty × IT interaction was obtained in the initial ANOVA [$F(2, 38) = 5.07$, $p < .05$]. Subsidiary target/new contrasts revealed three-way interactions in both conditions, indicating that target positivities exhibited a mid-central (CZ) maximum and an additional left-parietal elevation at P3 (see Figure 2). The non-target/new contrasts revealed reliable effects in the

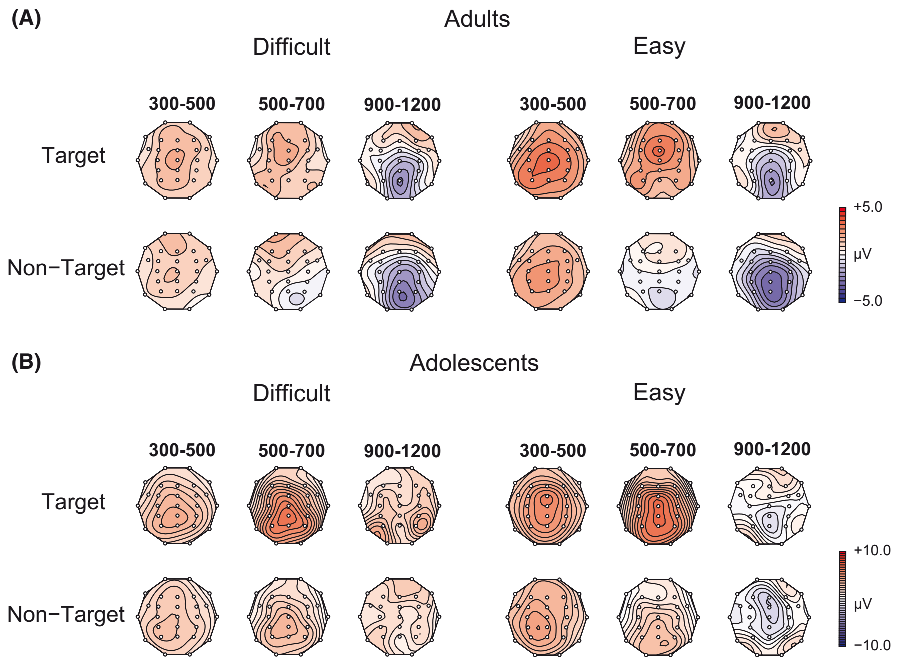

Figure 2 *Topographic maps showing the scalp distributions of the ERP old/new effects for targets and for non-targets for adults (A) and adolescents (B) in both difficulty conditions. All maps were computed on the basis of difference scores obtained by subtracting mean amplitudes of the ERPs elicited by new words from those elicited by targets and non-targets. Data are shown for the 300–500, 700–500, and 900–1200 ms time-windows.*

Table 2 *Outcomes of the paired contrasts between ERPs elicited by correct judgments to targets, non-targets, and new words over the 300–500, 500–700, and 900–1200 ms time-windows for adults*

		300–500		500–700		
Contrast	*df*	Difficult	Easy	Difficult	Easy	900–1200[a]
Target vs. new						
IT	1,19	9.69**	50.13***	8.51**	18.22***	*ns*
IT × AP	2,38	*ns*	*ns*	*ns*	*ns*	14.65***
IT × LAT	2,38	*ns*	*ns*	*ns*	*ns*	*ns*
IT × AP × LAT	4,76	*ns*	3.87**	3.30*	3.49*	3.52*
Non-target vs. new						
IT	1,19	9.07**	21.55***	ns	*ns*	10.64**
IT × AP	2,38	*ns*	*ns*	8.14**	*ns*	14.02***
IT × LAT	2,38	*ns*	*ns*	4.8*	*ns*	9.20**
IT × AP × LAT	4,76	*ns*	*ns*	*ns*	*ns*	3.73*
Target vs. non-target						
IT	1,19	*ns*	10.60**	5.20*	33.18***	6.43*
IT × AP	2,38	*ns*	*ns*	5.69**	*ns*	*ns*
IT × LAT	2,38	*ns*	*ns*	*ns*	*ns*	*ns*
IT × AP × LAT	4,76	3.41*	*ns*	*ns*	*ns*	*ns*

Note: IT = item type, AP = anterior/posterior, LAT = laterality.
[a] All contrasts were collapsed across both difficulty conditions.
$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

difficult condition only, where non-targets exhibited a reliable positivity across frontal sites ($p < .05$). The target/non-target contrasts revealed an IT × AP interaction in the difficult condition, reflecting greater target positivities at parietal sites ($p < .05$). In the easy condition, this target/non-target effect was found across locations.

For adolescents, the initial ANOVA revealed no Difficulty by IT interactions (p-values $> .48$). The target/new and the non-target/new contrasts collapsed across both conditions revealed IT × AP interactions, indicating the parietal maxima of both old/new effects (see Figure 2). For targets, the IT × Laterality interaction indicates additional midline maxima. The target/non-target contrast revealed greater positivities for targets across sites.

900–1200 ms

For adults, both target/new and non-target/new contrasts revealed three-way interactions, reflecting reliable

Table 3 *Outcomes of the paired contrasts between ERPs elicited by correct judgments to targets, non-targets, and new words over the 300–500, 500–700, and 900–1200 ms time-windows for adolescents*

Contrast	*df*	300–500[a]	500–700[a]	900–1200	
				Difficult	Easy
Target vs. new					
IT	1,17	71.33***	31.95***	6.63*	*ns*
IT × AP	2,34	*ns*	10.16***	*ns*	*ns*
IT × LAT	2,34	7.63**	3.50*	*ns*	*ns*
IT × AP × LAT	4,68	*ns*	*ns*	*ns*	*ns*
Non-target vs. new					
IT	1,17	73.18***	16.35***	4.63*	*ns*
IT × AP	2,34	*ns*	5.13*	*ns*	*ns*
IT × LAT	2,34	8.47**	*ns*	*ns*	4.85*
IT × AP × LAT	4,68	*ns*	*ns*	*ns*	*ns*
Target vs. non-target					
IT	1,17	*ns*	16.21**	*ns*	*ns*
IT × AP	2,34	*ns*	*ns*	*ns*	*ns*
IT × LAT	2,34	*ns*	*ns*	*ns*	*ns*
IT × AP × LAT	4,68	*ns*	*ns*	*ns*	*ns*

Note: IT = item type, AP = anterior/posterior, LAT = laterality.
[a] All contrasts were collapsed across both difficulty conditions.
*$p < .05$; **$p < .01$; ***$p < .001$.

negativities for targets and non-targets with a maximum at PZ (p-values < .01), in addition to robust right-frontal old/new effects for targets at F4 ($p < .05$). The target/non-target contrast revealed greater negativities for non-targets across electrodes. Neither of these effects interacted with Difficulty (p-values > .16).

For adolescents, a Difficulty × IT × AP interaction [$F(4, 68) = 3.50$, $p < .05$] was obtained. While in the difficult condition robust old/new effects were obtained for targets and non-targets across locations, no significant ERP effects were observed in the easy condition (p-values > .18).

Summary

From 300 to 500 ms, adults and adolescents showed similar early frontal old/new effects, the putative ERP correlate of familiarity, for targets and non-targets in both conditions. The age groups showed different patterns of ERP effects, however, in the 500–700 ms time-window. For adults, only targets elicited parietal old/new effects, the ERP correlate of recollection. Notably, no ERP effects of non-target recollection were obtained in either condition for adults, suggesting the engagement of a target-selective retrieval strategy in both conditions. However, the results nonetheless suggest that the processing of non-targets was influenced by task difficulty for adults, as evidenced by a selective non-target old/new effect between 500 and 700 ms with an unexpected frontal topography in the difficult condition. Adolescents, by contrast, showed parietal old/new effects for targets and non-targets in both conditions, confirming our hypothesis that the adolescents do not show evidence of target-selective recollection even when task difficulty is low. From 900 to 1200 ms, adults showed right-frontal effects of post-retrieval monitoring for targets. These were accompanied by mid-parietal LPNs for both targets and non-targets, presumably reflecting the search for attribute conjunctions from the prior study phase. Conversely, adolescents showed a less refined pattern of ERP effects over this epoch, as old/new effects showed a widespread distribution across locations and no LPNs were observed.

Topographic analyses

These were performed in order to determine, within each age group, whether the scalp distributions of the old/new effects reported above varied across time-windows and can therefore be attributed to functionally distinct retrieval processes (Wilding, 2006). The analyses were conducted separately for targets and non-targets upon the old/new subtraction data shown in Figure 2, and included data from 15 electrode sites (F7, F3, FZ, F4, F8, T7, C3, CZ, C4, T8, P7, P3, PZ, P4, P8). In order to avoid confounds with differences in the magnitudes of effects across adjacent time-windows, subtraction data were rescaled prior to analysis (McCarthy & Wood, 1985). All analyses included the factors of Time-window (2 levels), AP, Laterality (5 levels), and Difficulty. Their outcomes are presented in Table 4.

Adults

Reliable three-way interactions between Time-window, AP, and Laterality for all contrasts indicated that the topographies of all old/new effects differed qualitatively across time. Target and non-target old/new effects were broadly distributed from 300 to 500 ms, before additional left-parietal enhancements emerged for targets, and frontal foci emerged for non-targets in the 500–700 ms interval. From 900 to 1200 ms, target old/new effects at anterior sites became focused over the right hemisphere, while at mid-parietal locations negative-going foci were evident for targets and non-targets. Additionally, for non-targets these three-way interactions were modulated by Difficulty. Further comparisons revealed that, whereas difficult and easy non-target old/new effects did not differ during either the 300–500 or the 900–1200 ms intervals, a marginal Difficulty × AP × Laterality interaction [$F(8, 152) = 1.91$, $p = .062$] suggested that the effect exhibited a stronger frontal focus in the difficult than in the easy condition during the 500–700 ms time-window.

Adolescents

The 300–500 vs. 500–700 ms contrast revealed reliable three-way interactions for targets and non-targets, indicating the stronger parietal focus of the old/new effects in the second compared to the first time-window. The 500–700 vs. 900–1200 ms contrast revealed an interaction between Time-window and Laterality for

Table 4 *Outcomes of the topographical comparisons between the ERP old/new effects in the consecutive time-windows for both age groups*

	Adults		Adolescents	
	300–500 vs. 500–700	500–700 vs. 900–1200	300–500 vs. 500–700	500–700 vs. 900–1200
Target/New				
TW × AP	*ns*	^{2,38} 8.62**	^{2,34} 7.01*	*ns*
TW × LAT	*ns*	^{4,76} 14.40***	*ns*	*ns*
TW × AP × LAT	^{8,152} 4.35**	^{8,152} 6.32***	^{8,136} 2.68*	*ns*
TW × AP × LAT × DIF	*ns*	*ns*	*ns*	*ns*
Non-target/New				
TW × AP	^{2,38} 5.85*	*ns*	^{2,34} 7.42**	*ns*
TW × LAT	*ns*	^{4,76} 5.86**	^{4,68} 3.80*	^{4,68} 8.20**
TW × AP × LAT	^{8,152} 4.54**	^{8,152} 5.27**	^{8,136} 2.73*	*ns*
TW × AP × LAT × DIF	^{8,152} 2.58*	^{8,152} 2.87*	*ns*	*ns*

Note: TW = time-window, AP = anterior/posterior, LAT = laterality, DIF = difficulty.
Degrees of freedom are shown in superscript.
*$p < .05$; **$p < .01$; ***$p < .001$.

non-targets, reflecting a decline of the old/new effect across the midline in the 900–1200 ms time-window, a change that appeared to be especially pronounced in the easy condition (see Figure 2).

Relationship between ERPs and WMC

The predictions regarding the relationship between the ERP target/non-target diverge and WMC were tested via separate correlation analyses in both age groups for both conditions. These analyses were performed on the target/non-target difference amplitudes between 500 and 700 ms at parietal electrodes (P3, Pz, P4). For adults, significant positive correlations between these measures were obtained at P3 and PZ in the easy condition but not in the difficult condition (see Table 5). By contrast, no significant relationships were revealed for the adolescents (*p*-values > .14). Figure 3 illustrates this pattern of relationships at the P3 electrode. It shows that the amplitude of the ERP target/non-target difference increased with Operation Span scores only for adults in the easy condition. Notably, all correlations for adolescents remained non-significant when two participants whose ERP difference amplitudes exceeded the group mean by more than 1.5 *SD*s were removed (*R*-values < .11), suggesting that the absence of correlations cannot be attributed to the relatively large variability in the adolescents' ERP data (see Figure 3).

Table 5 *Pearson's R-values relating ERP target/non-target difference amplitudes (target – non-target) at parietal electrode sites with Operation Span scores for both age groups in both conditions*

	Adults		Adolescents	
Site	Difficult	Easy	Difficult	Easy
P3	.12	.49*	.31	.05
PZ	−.05	.54*	.28	.19
P4	−.01	.30	.35	.18

Note: All significance tests were two-tailed.
*$p < .05$.

Discussion

As expected, participants in both age groups were better at discriminating targets from non-targets and new words in the easy compared to the difficult condition. Reduced task difficulty in the easy condition also accelerated the speed of memory judgments for targets and new words in both age groups. These data suggest that our difficult/easy manipulation resulted in relatively lower strategic control demands in the easy condition. Furthermore, consistent with our prediction, memory accuracy improved with age. This effect was of similar magnitude in both conditions and particularly pronounced for target/non-target discrimination. In order to elucidate the mechanisms that underlie this age-related improvement in source memory performance, we analyzed ERP effects associated with targets and non-targets in both age groups.

For adults, reliable left-parietal old/new effects were obtained for targets in both conditions while non-targets failed to elicit these effects in either condition. Similarly, late right-frontal effects were elicited by targets only, indicating that the adult participants engaged in post-retrieval monitoring operations of information about targets but not non-targets. These results are consistent with the view that the adults adopted a target-selective retrieval strategy and in turn inhibited the recollection of non-target information even when strategic control demands were high.

These results obtained for adults suggest that the likelihood of discrimination, and/or the degree of similarity between targets and non-targets does not solely determine the conditions under which strategic retrieval will occur. It is noteworthy that previous investigations in which color information was used for the target/non-target distinction have revealed reliable old/new effects for non-targets (Cycowicz *et al.*, 2001a; de Chasteleine *et al.*, 2007; Wilding *et al.*, 2005). These effects have been attributed to the high degree of source similarity when color information is used, possibly precluding the restriction of recollection to targets only (Wilding *et al.*,

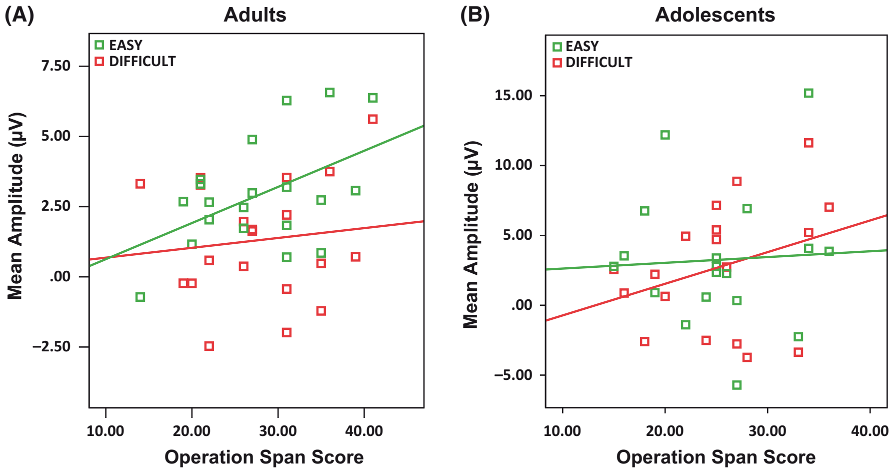

Figure 3 *Scatterplots showing the relationships between the Operation Span scores and the ERP target/non-target difference amplitudes (target – non-target) from 500 to 700 ms at P3 for adults (A) and adolescents (B) in both difficulty conditions.*

2005). While color information was also used here, our study differs from the above-mentioned experiments in that the words in our study were encoded elaboratively, which might have generated contextual details that facilitated source discrimination. Consistent with this account are findings from a study by Herron and Wilding (2005) in which targets and non-targets were encoded elaboratively and target accuracy was reduced in one condition with an increased study–test interval. Similarly to the present results, targets but not non-targets elicited left-parietal and right-frontal old/new effects in either condition. It therefore appears that selective retrieval can occur despite a close correspondence between different sources of information, for example when elaborative encoding provides a sufficient number of discriminative contextual characteristics.

The critical contribution of the present study comes from the fact that for adolescents, our analyses revealed reliable parietal ERP old/new effects for targets as well as for non-targets in both conditions. This is consistent with our prediction that the adolescents rely on recollection of information associated with targets and non-targets, and in this way show less evidence of target-selective retrieval compared to adults. Importantly, adolescents showed ERP correlates of non-target recollection in the easy condition, while adults did so in neither of the two. As memory performance of adolescents in the easy condition was equal to that of adults in the difficult condition, it appears that the age-related difference in selective recollection observed here does not depend on the difficulty of the task. This in turn arguably provides strong support for the view that the ability to selectively recollect target information at the expense of non-target information is generally immature in early adolescence.

These data fit into and extend the larger picture from previous research which suggests that adolescence is critical for the development of those memory processes that depend on strategic control (Cycowicz, Fiedman & Duff, 2003; Cycowicz, Friedman, Snodgrass & Duff, 2001b; Shing *et al.*, 2008; Paz-Alonso, Ghetti, Donohue, Goodman & Bunge, 2008). For example, Shing *et al.* (2008) introduced a model of episodic memory development that postulates that higher-level strategic memory processes that depend on the PFC follow a protracted developmental trajectory compared to lower-level associative processes supported by the hippocampus. Considerable promise for characterizing the particular strategic processes that are likely to play a role in the age-related differences observed here comes from several frameworks that identify the separate control processes which operate at distinct retrieval stages, including cue processes that are engaged prior to retrieval in order to specify task-dependent features of the retrieval cue (e.g. Moscovitch & Winocur, 2002). In particular, cue specification processes are assumed to assist selective retrieval by constraining and maintaining internal representations of the retrieval cue, in order to specify which parts of the total complex of memory traces that is related to the cue should be accessed (Burgess & Shallice, 1996; Mecklinger, 2010). One possibility, therefore, is that the age-related differences observed in the ERPs reflect the fact that adolescents are less efficient than adults in engaging cue specification processes that facilitate selective recollection. By this, the present findings confirm and extend current models of memory development (e.g. Shing *et al.*, 2008), as they suggest that one aspect of what characterizes memory development during adolescence is a change in the ability to engage the control processes necessary for focusing retrieval on target information.

A further reason to take this view follows from the finding that the size of the differences between the parietal target and non-target ERP old/new effects was correlated positively with WMC in adults but not in adolescents, even though this correlation was evident in the easy condition only (but see discussion below). Notably, this age difference observed in the correlations investigated here suggests that not only are adults more likely than adolescents to prioritize recollection of target information over non-target recollection but that the extent to which this prioritization occurs is more systematically related to cognitive control resources in adults. Taking into account the fact that adolescents did not differ from adults in mean WMC in the present study, one interpretation of the current data is that while the resources measured in WMC are in place in early adolescence, what develops during adolescence is the ability to make use of these resources for the strategic control of recollection. In line with this is the observation that as cognitive control does not constitute a unitary construct, different memory-related strategic processes show divergent developmental trajectories, depending upon the amount and type of control required (Luciana, Conklin, Hooper & Yarger, 2005; Luna, Garver, Urban, Lazar & Sweeney, 2004; De Luca, Wood, Anderson, Buchanan, Proffitt, Mahoney & Pantelis, 2003).

A complementary account of the present data can be derived from the recently made proposal that inhibition is the mechanism responsible for the attenuation of parietal non-target ERP old/new effects relative to target effects (Wilding & Herron, 2006). On the basis of a 'resource model of inhibition' that relates inhibition to cognitive resources that are available for controlling interference (Conway & Engle, 1994), evidence consistent with the inhibition account is provided by the correlations between the critical ERP contrasts and WMC reported here and elsewhere (Elward & Wilding, 2010). An interesting possibility to be addressed in future studies, therefore, is whether age-related changes in selective retrieval occur in association with changes in the ability to regulate competing memory traces through inhibitory control.

In addition to the implications of the pattern of parietal old/new effects in the two age groups discussed so far, the present study revealed several further ERP modulations that can be associated with different aspects of episodic retrieval processing. One such modulation was observed in the 300–500 ms time-window, where both age groups showed similar early mid-frontal old/new effects. According to the prevailing view, this early frontal effect reflects familiarity-based remembering that arises as a function of the global similarity between study and test items (Mecklinger, 2006). Support for a familiarity account of the current effects comes from the topographic analyses which provided evidence that these effects are functionally distinct from recollection as indexed in the subsequent parietal old/new effects (Wilding, 2006). Even though the familiarity effects observed here most likely result from mere item repetition, a further contribution may have come from the encoding procedure used in our study which required participants to imagine study items in the source color. A similar procedure has previously been employed to promote 'unitization' of item and source information during encoding, and in this way to enhance the contribution of familiarity to source memory (Diana *et al*., 2008). Regardless of which of both accounts best explains the data, one conclusion supported by the present results is that because both age groups showed similar early mid-frontal old/new effects, familiarity-based remembering was unaffected by the strategic operations that the adults employed with greater success to exert control over recollection. This conclusion receives additional support from data showing that recollection undergoes more developmental change during childhood and adolescence than does familiarity, as reported by several behavioral studies in which a variety of operational definitions of recollection and familiarity were used (Anooshian, 1999; Billingsley, Smith & McAndrews, 2002; Ghetti & Angelini, 2008; Ofen, Kao, Sokol-Hessner, Kim, Whitfield-Gabrieli & Gabrieli, 2007).

A further disparity between the ERPs in both age groups that is relevant for the present investigation is based on the observation of a number of old/new effects that were evident for adults only. Common to both difficulty conditions were the mid-parietal LPNs for targets and non-targets that were evident over the 900–1200 ms time-window, and which were accompanied by right-frontal old/new effects for targets. As noted in the Introduction, these effects have been associated with different aspects of post-retrieval processing (Hayama *et al*., 2008; Johansson & Mecklinger, 2003). In this way, the observation that these effects were absent in adolescents agrees with previous evidence for prolonged developmental refinements in the ERP correlates of post-retrieval monitoring and evaluation (Cycowicz *et al*., 2003; de Chastelaine *et al*., 2007; Sprondel *et al*., 2011).

Finally, one ERP modulation for adults that diverged between the two difficulty conditions was observed between 500 and 700 ms, where non-targets elicited an unexpected frontal old/new effect in the difficult condition. A possible functional account of this effect may be derived from memory exclusion paradigms that have shown that retrieval difficulty influences ERP activity elicited by new items (Dzulkifli, Sharpe & Wilding, 2004; Rosburg, Mecklinger & Johansson, 2011a). The assumption underlying these paradigms is that differences between new item ERPs across tasks with different retrieval demands can be attributed to the above discussed cue specification processes that are engaged depending upon the particular task requirements (Mecklinger, 2010). For example, Rosburg *et al*. (2011a) demonstrated a left-frontal ERP difference between new test items when contrasted across two different target designations that differed in task difficulty. Critically, the amplitude of this effect was largest for participants with the highest relative task difficulty as indexed by the greatest difference in memory performance between the two conditions. These results were taken to indicate that the cue specification processes indexed in this type of ERP contrast need to be engaged to a greater extent when demands on retrieval control increase (Rosburg *et al*., 2011a). Therefore, although these latter data were obtained with different operational definitions of strategic retrieval, on the basis of the similarity to the present results regarding the influence of task difficulty on

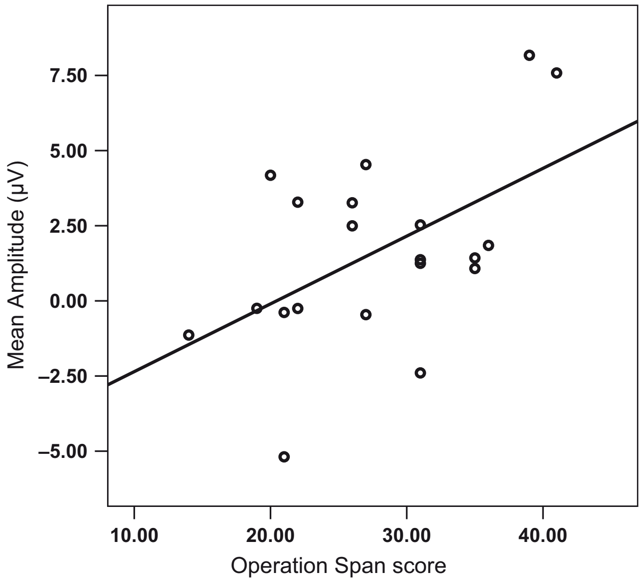

Figure 4 *Scatterplot showing the relationship between the Operation Span scores and the ERP non-target/new difference amplitude (non-target – new) between 500 and 700 ms at F3 for adults in the difficult condition.*

frontal ERP effects, they may account for the current non-target effect which might reflect the greater demands on cue specification. Following these lines of reasoning, we hypothesized that the amplitude of the ERP non-target/new difference should be related to the availability of control resources as indexed by WMC. A post-hoc correlation analysis revealed significant positive correlations between both measures at all three frontal electrodes (*R*-values = .52, .46, and .45 for F3, Fz, and F4, respectively, *p*-values < .05; see Figure 4). We tentatively propose, therefore, that the frontal non-target effect in the difficult condition reflects a capacity-limited control process, possibly the stronger engagement of cue specification processes in order to discriminate targets from non-targets.

To summarize, the current study revealed three main findings that substantiate and expand upon earlier findings regarding the development of strategic retrieval. First, our data show that the ability to focus recollection on one kind of task-relevant information in order to make a binary source judgment matures only after or during late adolescence. Second, the age-specific pattern of correlations between the ERPs and WMC suggests that adults can allocate their cognitive resources to strategic recollection more efficiently than adolescents. Finally, the results confirm previous evidence for immaturity in the networks underlying post-retrieval control in early adolescence. Together, these findings fit with the evidence for prolonged functional specialization within neurocognitive control networks (Luna *et al.*, 2010) and also extend the latter line of evidence by uncovering neural correlates of maturation in the control of episodic memory retrieval.

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