Research Report

ERP evidence for successful voluntary avoidance of conscious recollection

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ABSTRACT

We investigated neurocognitive processes of voluntarily avoiding conscious recollection by asking participants to either attempt to recollect (the Think condition) or to avoid recollecting (the No-Think condition) a previously exposed paired associate. Event-related potentials (ERPs) during Think and No-Think trials were separated on the basis of previous learning success versus failure. This separation yielded temporal and topographic dissociations between early ERP effects of a Think versus No-Think strategy, which were maximal between 200 and 300 ms after stimulus presentation and independent of learning status, and a later learning-specific ERP effect maximal between 500 and 800 ms after stimulus presentation. In this later time-window, Learned Think items elicited a larger late left parietal positivity than did Not Learned Think, Learned No-Think, and Not Learned No-Think items; moreover, Learned No-Think and Not Learned Think items did not differ in late left parietal positivity. Because the late left parietal positivity indexes conscious recollection, the results provide firm evidence that conscious recollection of recollectable information can be voluntarily avoided on an item-specific basis and help to clarify previous neural evidence from the Think/No-Think procedure, which could not separate item-specific from strategic processes.

INTRODUCTION

1. Can conscious recollection be voluntarily avoided? Evidence from the Think/No-Think procedure

There are a lot of things in life that we would prefer not to think about, including memories from our past that may be painful, embarrassing, or simply distracting. Whether we are actually able to avoid retrieving such memories is a controversial issue and one that has considerable clinical relevance. Some research has suggested that we cannot avoid unwanted thoughts because, ironically, checking whether avoidance is successful puts the thought at the focus of attention (e.g., Wegner, 1994). However, more recent research suggests that avoidance of an unwanted memory can be successful because that memory can later become inaccessible as a consequence of such avoidance (Anderson and Green, 2001). The latter evidence, however, is only indirect because the successful avoidance of the unwanted memory during training is inferred from the greater later forgetting that occurs as a result.

A critical question, therefore, is whether we are truly able to avoid conscious recollection of recollectable material, at the
time when the attempted avoidance occurs. This question is very difficult to address scientifically with standard behavioral or subjective report techniques. However, investigations of the brain correlates of conscious recollection during attempts to recollect versus avoid recollecting learned information have considerable potential to shed light on the issue. Anderson et al. (2004) investigated the relevant brain regions in a functional magnetic resonance imaging (fMRI) study using the Think/No-Think paradigm (Anderson and Green, 2001). In this paradigm, participants initially learn a list of weakly associated word pairs (the study phase). They then receive the first words from a subset of studied pairs as cues and are asked either to recall the associated words (the Think condition) or to completely prevent the associated words from entering consciousness (the No-Think condition). This training phase (henceforth termed the Think/No-Think phase) is followed by a final cued recall test. In this final test, participants are often impaired at recalling the No-Think associates compared to associates in a Baseline condition, which were initially studied, but neither recalled nor avoided during the Think/No-Think phase. The No-Think associates thus often demonstrate a memory impairment over and above simple forgetting over time. The forgetting inferred to result from successful avoidance of recollection for No-Think items in the Think/No-Think phase (Anderson and Green, 2001), but the fMRI data obtained during the Think/No-Think phase provided much more direct evidence of such avoidance.

Brain regions showing a greater hemodynamic response during No-Think compared to Think trials included bilateral dorsolateral and ventrolateral prefrontal regions, anterior cingulate cortex, and several premotor regions. By contrast, the hippocampus, as well as areas of left parietal cortex and bilateral frontopolar cortex, showed a smaller hemodynamic response during No-Think compared to Think trials. The prefrontal regions that showed increased activation during No-Think trials have been implicated in processes such as inhibiting task-irrelevant information (Knight et al., 1999), and the anterior cingulate cortex is also thought to play an important role in cognitive control (e.g., Carter et al., 1999; Magni et al., 2006). Anderson et al. (2004) therefore interpreted the increased activation in these areas as reflecting an active inhibitory control function responsible for avoidance of recollection. On the other hand, the hippocampus has been implicated in conscious recollection both by neuroimaging (e.g., Eldridge et al., 2000) and lesion studies (e.g., Eichenbaum, 1997), and so has the posterior parietal cortex (e.g., Wagner et al., 2005). Anderson et al. (2004) therefore interpreted the smaller hemodynamic response in these areas on No-Think trials as evidence of reduced conscious recollection of the No-Think associates during the Think/No-Think phase, at the time when attempted avoidance of recollection occurred.

However, a significant limitation of the Anderson et al. (2004) fMRI design is that it was not possible to distinguish between the neural correlates of the strategy of recollecting or avoiding recollection, and the neural correlates of item-specific recollection versus avoidance of recollection. This limitation stems from the simple contrast between Think and No-Think trials during the Think/No-Think phase and is compounded by the relatively poor time resolution of fMRI. Furthermore, it was not possible to establish whether conscious recollection (as indicated by activity in relevant brain areas, such as the hippocampus) was simply reduced on No-Think trials, or whether conscious recollection was diminished to the point where there was little neural evidence of recollection for No-Think items.

In the current research, we modified the experimental design employed by Anderson et al. (2004) in order to address both limitations and used event-related potentials (ERPs) to reveal brain activity. ERPs have some considerable advantages over fMRI, in that they can separate strategic and item-specific processes in real time during an experimental trial. We addressed the difference between strategic and item-specific processes by separating items based on learning success versus failure in the study phase of the experiment, as assessed by a criterial test at the end of that phase. During the subsequent Think/No-Think phase, in which ERPs were recorded, participants received cues corresponding to originally learned and originally not learned associates, with either Think or No-Think instructions, resulting in four ERP conditions. Effects on ERPs of the Think versus No-Think instructions that were common to originally learned and not learned associates should primarily reflect strategic processes because item-specific memory was absent for the not learned associates. By contrast, effects on ERPs of the Think versus No-Think instructions that occurred only for originally learned associates should primarily reflect item-specific processes. We elaborate on this strategic versus item-specific separation in Section 1.2. A further advantage of taking original learning into account was that we could compare ERPs for No-Think associates originally learned with ERPs for Think and No-Think items not originally learned, with the latter being very unlikely to be recollectable during the Think/No-Think phase. These comparisons permitted us to examine whether there was any neural evidence of item-specific recollection for the No-Think learned items.

A number of behavioral experiments using the Think/No-Think procedure now indicate that No-Think associates are not always more poorly recalled than baseline associates in the final cued recall test following the Think/No-Think phase (e.g., Bulevich et al., in press; Hertel and Gerstle, 2003; Hertel and Calcaterra, 2005), and in the experiment reported here, we also did not find above-baseline forgetting for No-Think associates in the final cued recall test. The absence of a subsequent forgetting effect, however, does not limit the value of the Think/No-Think procedure for examining whether recollection can be voluntarily avoided during No-Think trials and in fact turns into a virtue in this respect for an initial investigation. It means that the issue can be examined unconfounded by ERP differences between Think and No-Think trials in terms of processes that might be involved in producing differential later forgetting. Moreover, we could further ensure that our analysis was not complicated by differences in later forgetting by examining ERPs during the Think/No-Think phase only for items that either were successfully learned during the initial study phase and successfully recalled in the final cued recall test, and for items that were not learned during the initial study phase, and not recalled in the final cued recall test. This method of classifying the ERPs meant that, for the originally learned associates in the No-Think condition, we could be confident that participants could have brought the relevant associate to mind during the No-Think trials had they tried to
do so because they were able to recollect those associates successfully later.

In summary, the current ERP analysis addresses whether people are able to voluntarily avoid conscious recollection of demonstrably recollectable information, a question that requires no subsequent forgetting effect for validity and that in fact is more validly initially examined in the absence of a subsequent forgetting effect. Thus, we emphasize that we make no claim in the current article to demonstrate ERP differences related to processes causative of later forgetting.

1.2. Evidence regarding voluntary control over ERP effects relating to conscious recollection, and advantages of the Think/No-Think procedure

ERP research on memory retrieval is now sufficiently advanced that particular ERP effects (defined by timing and scalp topography) can act as markers of memory processes (Rugg, 1995). The correlate of conscious recollection is a positive shift of the ERP at parietal regions, typically left-lateralized, and maximal approximately 400 to 800 ms after stimulus presentation. This effect was first found in old/new recognition tasks (Paller and Kutas, 1992; Rugg, 1995; Smith, 1993; Smith and Halgren, 1989), in which correctly recognized old items elicit greater left parietal positivity compared to old but unrecognized items and correctly rejected new items. The effect is larger if participants, in addition to recognizing the items, can also correctly identify their source (Trott et al., 1999; Wilding, 2000; Wilding and Rugg, 1996), and if the items are associated with “remember” (contextual recollection) rather than “know” (familiarity) judgments (Duzel et al., 1997; Smith, 1993; Trott et al., 1999). Moreover, the effect is absent in patients with impaired recollection due to hippocampal lesions (Duzel et al., 2001), and it has been suggested to originate from recollection-related activity in hippocampal-parietal cortical networks (e.g., Curran et al., 2006). Most relevant here, the left parietal positivity is also found in associative cued recall tasks, for recognized recall cues for which recall of the associate is successful (Rugg et al., 1996). Although typically known as the left parietal old/new effect, we henceforth refer to it as the left parietal episodic memory effect, in view of the strong evidence linking the effect with conscious recollection.

Important preliminary evidence regarding the voluntary controllability of the left parietal episodic memory effect has been provided by recent studies that have employed modified recognition tests, in which items that have been studied (old items) are intermixed with new items, but only a subset of the old items are designated as to-be-recognized targets at test (e.g., Dywan et al., 1998, 2001, 2002; Dzulkiﬁ and Wilding, 2005; Herron and Rugg, 2003a, 2003b; Herron and Wilding, 2005; Wilding et al., 2005). For example, participants may be instructed to respond “old” to items from one previously presented list (designated as targets) and “new” to items from another previously presented list (designated as non-targets) as well as to truly new items. When the probability of correctly recollecting targets is high, the left parietal episodic memory effect occurs for targets compared to new words, but not for non-targets compared to new words. If memory for the target information is poor (e.g., when there has been less elaborative encoding in the study phase), the left parietal episodic memory effect occurs for both targets and non-targets compared to new words.

The interpretation of these findings has been that, when target memory is good, conscious recollection is strategically controlled to occur in response to targets and not to non-targets (Herron and Rugg, 2003b) because participants can successfully perform the task by selectively recollecting information from the target study episode only and making an “old” response only to items for which recollection of target source information was successful. The diagnostic value of this strategy would, however, decrease when the probability of recollecting the target episode is low because participants can only successfully perform the task by recollecting information from both the target and non-target episodes.

These findings provide some evidence that conscious recollection of old non-target information can be strategically avoided when target memory is good. However, the target/non-target paradigm does not explicitly ask participants to control their recollection and thus only provides indirect evidence regarding such strategic control. In addition the old target and old non-target items are inevitably encoded under different conditions (in order that participants can distinguish them at test), meaning that the relevant ERP differences cannot be conclusively ascribed to the operation of strategic processes at retrieval. Target and non-target items may, for example, simply be differentially memorable owing to encoding differences or retention interval differences (although see Wilding et al., 2005 for results from a target/non-target task that are unlikely to reflect such differences).

The Think/No-Think procedure used here, by contrast to the target/non-target procedure, has the considerable advantage that participants are explicitly instructed to recollect or avoid recollection during the Think/No-Think phase, so that strategic processes are directly manipulated and that Think and No-Think items are previously encoded under identical conditions. In addition, our version of this procedure permitted us to explicitly distinguish the ERP correlates of strategies of selective recollection from the ERP correlates of the outcomes of these strategies, namely successful actual recollection or successful actual avoidance of recollection.

To accomplish this separation, we classified paired associates presented in the study phase as initially learned or not learned, based on performance in a criterial cued recall test conducted at the end of that phase (with just over half of the items being initially learned, on average). Items entered the Learned ERP condition only if the participant had initially learned the item in the study phase and could also recall it in the final cued recall test, and entered the Not Learned ERP condition only if the participant initially failed to learn the item in the study phase and also could not recall it in the final cued recall test. ERPs for Think and No-Think trials in the intervening Think/No-Think phase were compared as a function of whether items were classified as Learned or Not Learned, resulting in four critical ERP conditions.

Differences between ERPs for Think and No-Think trials that were independent of the learning status of the items should be primarily due to task-related strategic processes. That is, if such differences were present for Not Learned as well as Learned items, they should not primarily reflect item-
specific memory processes because item-specific memory was absent for the Not Learned items. By contrast, ERP differences between Think and No-Think trials that were present only for Learned items, and not for Not Learned items, should primarily reflect successful recollection or successful avoidance of recollection of specific items.

This analysis is advantageous for the present purpose of investigating voluntary avoidance of recollection because ERPs for items that are initially learned in the study phase, but forgotten on the final cued recall test, are excluded. Thus, for the items in the Learned No-Think condition, we could be confident that the participants could recollect the relevant item during the Think/No-Think phase had they tried to do so because they could successfully recall that item later. Moreover because there was no significant difference in subsequent forgetting between Learned Think and Learned No-Think items, we could also be assured of similar trial numbers (and therefore similar signal-to-noise ratio in the ERPs) for these two ERP conditions and that ERP differences between these conditions were not confounded by processes leading to differential subsequent forgetting on the final cued recall test.

1.3. Predictions

Successful voluntary avoidance of recollection predicts a reduction in the left parietal episodic memory effect for the Learned No-Think ERP condition compared with the Learned Think ERP condition. Such a Think versus No-Think difference should be much less apparent for the Not Learned ERP conditions, indicating an item-specific strategic control effect. The extent of success in avoiding item-specific recollection can be assessed by comparing the left parietal episodic memory effect for the Learned No-Think ERP condition with the corresponding effect for the Not Learned Think and the Not Learned No-Think ERP conditions. Complete success in avoiding item-specific recollection in the Learned No-Think condition predicts no difference between these three ERP conditions.

ERPs effects of Think versus No-Think condition that generalize across the Learned and Not Learned conditions should primarily reflect task-related strategic processes, such as the attempt to recollect versus the attempt to avoid recollection. Here the ERP predictions are less clear. However, if an ERP correlate of task-related strategic processes could be separated temporally and topographically from the predicted modulation of the left parietal episodic memory effect, it would reinforce the conclusion that the latter modulation primarily reflected an item-specific strategic control effect. Furthermore, isolating an ERP correlate of a strategy of attempting to recollect versus attempting to avoid recollection would assist considerably in future attempts to clarify the nature of such a strategy (see, e.g., Hertel and Calcabella, 2005).

2. Results

2.1. Behavioral results

In the initial criterial test of learning (cued recall test) at the end of the study phase, 55% of associate-words were recalled on average (range 33% to 78%; SEM = 2.9%); therefore, the remaining 45% were not recalled on average. The remaining statistics presented here relate to correct recall of associate-words in response to their respective cue-words in the final cued recall test and are expressed as percentages of the numbers of items recalled and not recalled in the initial criterial test (these final recall percentages being calculated on an individual-participant basis prior to averaging). Think and No-Think items were initially studied and appeared in the Think/No-Think phase intervening between the study phase and the final cued recall test; Baseline items were initially studied but did not appear in the intervening Think/No-Think phase.

For items recalled in the initial criterial test, there was a trend for Think items to be better recalled in the final cued recall test (mean accuracy = 92.57%, SEM = 1.65%) than Baseline items (mean accuracy = 88.22%, SEM = 2.42%, t(22) = 1.772, p = 0.09) and No-Think items (mean accuracy = 87.91%, SEM = 2.17%, t(22) = 2.097, p = 0.048; both contrast non-significant against Bonferroni-corrected α = 0.0167 for three comparisons). However, there was no significant reduction in accuracy in the final cued recall test for No-Think items compared to Baseline items (t(22) < 1). Thus, in common with prior studies by Bulevich et al. (in press), Hertel and Gerstle (2003), and Hertel and Calcabella (2005), the behavioral results do not reproduce findings (Anderson and Green, 2001; Anderson et al., 2004) of a transfer from voluntary avoidance of recollection during No-Think trials to an involuntary memory impairment in the final cued recall test.

Items that were recalled both in the initial criterial test and in the final cued recall test entered the Learned conditions for the ERP analysis. Thus, the absence of a final recall reduction for No-Think items meant approximately equal numbers of ERP observations for the Learned Think and Learned No-Think ERP conditions and that it was very likely that items in both conditions were recollectable during the Think/No-Think phase intervening between the study phase and the final cued recall test.

Items that participants failed to recall in the initial criterial test were unlikely to be successfully recalled in the final cued recall test (Think items, mean accuracy = 4.61%, SEM = 1.43%; No-Think items, mean accuracy = 5.70%, SEM = 1.46%; Baseline items, mean accuracy = 5.17%, SEM = 1.70%), and these means were not significantly different (all ts(22) < 1). These few items were excluded from the Not Learned ERP conditions, so that these conditions only contained items not recalled in both the initial and final tests. Thus, it was extremely unlikely that items in the Not Learned ERP conditions could be recollected during the Think/No-Think phase intervening between the study phase and the final cued recall test.

2.2. ERP results

ERPs reported here were recorded during the Think/No-Think phase intervening between the study phase and the final cued recall test, in which 20 cue-words were presented with Think instructions and 20 cue-words were presented with No-Think instructions, each cue-word being presented a total of 16 times. ERPs were averaged across these repeated presentations. Slightly more than half of the cue-words in each of the Think and No-Think conditions corresponded to Learned
items and slightly less than half corresponded to Not Learned items (for details see Sections 2.1 and 4.2). Fig. 1 shows, for the four resulting ERP conditions, the grand average waveforms recorded from electrodes at left and right fronto-polar sites, left and right frontal sites, left and right parietal sites, and left and right occipital sites. Inspection of the waveforms suggested qualitatively different ERP patterns in the earlier and later parts of the epoch. Therefore, two broad time-windows, 0 to 448 ms and 452 to 1000 ms, were employed for statistical analysis.

2.2.1. Early time-window (0–448 ms)
Initial data analysis of the early time-window was conducted using mean-centered spatiotemporal Task Partial Least Squares (Task PLS; Duzel et al., 2003, 2005; Lobaugh et al., 2001; McIntosh et al., 1996; McIntosh and Lobaugh, 2004). The PLS extracted one significant latent variable (LV) which accounted for 67.08% of the cross-block covariance (p < 0.001). The design salience of this LV is shown in Fig. 2, together with the bootstrap ratios of its electrode saliences to their standard errors (these being analogous to z scores). The principal contrast expressed by this LV was a main effect of the Think versus No-Think variable, but it also included a small main effect of the Learned versus Not Learned variable, and the timing of the effect was between 200 ms and approximately 300 ms post-stimulus, as indicated by the electrode saliences.

Follow-up analyses were performed at four sites that reliably showed the effects expressed by the significant LV in two time-windows (within the early time-window) that best captured the effects, 200 to 296 ms, and 300 to 396 ms. Two frontal (F3 left frontal/F4 right frontal) and two parietal (P3 left parietal/P4 right parietal) sites were selected on the basis of the PLS results, and Instruction (Think/No-Think; TNT) by Learning (Learned/Not Learned Status; LS) by Hemisphere (Left/Right; HM) by Anterior–Posterior (Anterior/Posterior; ANT) analyses of variance (ANOVAs) were conducted. These follow-up ANOVAs clarified the pattern indicated by the PLS analysis (degrees of freedom are 1 and 22 in all ANOVAs in all time-windows).

Fig. 1 – Grand mean ERPs for the four experimental conditions at left fronto-polar (FP1), right fronto-polar (FP2), left frontal (F3), right frontal (F4), left parietal (P3), right parietal (P4), left occipital (O1), and right occipital (O2) sites. The head-plot in the right bottom corner depicts the electrode locations (the coordinates of the electrode sites have been shifted towards the vertex in order to fit within the head radius). ERPs have been digitally filtered with a 15 Hz low-pass filter for visual presentation only.
Fig. 2 – Latent variable (LV) extracted by the PLS in the 0 to 448 ms time-window (cross-block covariance accounted for by this LV = 67.08%, p < 0.001). (A) Topographic maps of the bootstrap ratio of the electrode saliences of the LV to their standard error. These resemble z scores: values > 1.96 or < -1.96 are statistically significant at p < 0.05. Positive values indicate that electrode amplitudes are showing the pattern expressed in the design contrast in terms of more positive amplitudes for conditions that have a positive design score than conditions that have a negative design score, whereas negative bootstrap ratios indicate that electrode amplitudes are showing the reverse pattern. (B) The design contrast of the LV. This LV primarily expresses a significant main effect of Think versus No-Think instructions. The bootstrap ratios indicate that, from around 200 to 300 ms, the two Think conditions elicited reliably more positive ERPs than did the two No-Think conditions at anterior sites, whereas the two Think conditions elicited reliably more negative ERPs than did the two No-Think conditions at posterior sites.

From 200 to 296 ms post-stimulus there was a significant crossover interaction between TNT and ANT (F = 21.3, p < 0.001) revealed by a follow-up analysis to reflect a main effect whereby Think items were more positive than No-Think items at the two frontal sites (averaged across Hemisphere and Learning, t(22) = 4.07; p < 0.001), and a main effect in the reverse direction (No-Think more positive than Think items) at the two parietal sites (averaged across Hemisphere and Learning, t(22) = 3.77, p < 0.001). In a four-way ANOVA for the 300–396 ms time-window, the TNT × ANT interaction was no longer significant (F < 1). Instead, the only significant effect was an overall main effect of TNT (F = 4.9, p < 0.05), and although there were some trends for Learned items to have more positive mean amplitudes than Not Learned items, as also indicated by the PLS, in neither of the two time-windows did any effects involving LS as a factor reach significance.

In summary, in the earlier (0 to 448 ms) time-window, ERPs showed only task-related modulations caused by the Think versus No-Think variable. The most reliable differences occurred between 200 and 300 ms post-stimulus, when anterior sites showed more positive ERPs for the two Think than the two No-Think conditions, and posterior sites simultaneously showed more negative ERPs for the two Think than the two No-Think conditions.

### 2.2.2. Late time-window (452–1000 ms)

In the later time-window, a second mean-centered Task PLS extracted one significant LV which accounted for 76.44% of the cross-block covariance (p < 0.001). The design salience of this LV is shown in Fig. 3, together with the bootstrap ratios of its electrode saliences to their standard errors. The principal effect expressed by this LV was an interaction between the Think versus No-Think variable and the Learned versus Not Learned variable, such that the Learned Think condition differed from the other three conditions. The bootstrap ratios showed that Learned Think items elicited reliably more positive ERP amplitudes than the other three conditions at left parietal sites, maximal between around 500 ms and 800 ms post-stimulus, with a polarity reversal at right frontal sites that was of later (around 600 ms) onset.

Follow-up ANOVAs and simple comparisons were performed at the same four sites as in the earlier time-window using the same factorial design, in two time-windows (within the late time-window) that best captured the effects, 452 to 596 ms and 600 to 796 ms. The follow-up analyses confirmed the pattern indicated by the PLS (degrees of freedom were again 1 and 22 in all ANOVAs in all time-windows). The four-way ANOVA revealed significant three-way interactions between TNT × HM × ANT and LS × HM × ANT in the 452–596 ms (F = 10.7, p < 0.01; F = 14.2, p < 0.001) and 600–796 ms
(F=6.1, p<0.05; F=5.1, p<0.05) time-windows. The three-way ANOVAs revealed significant TNT×LS and LS×HM interactions at P3/P4 in the 452–596 ms time-window (F=17.8, p<0.001; F=12.4, p<0.01) and significant TNT×LS×HM interactions in the 600–796 ms time-window at F3/F4 (F=5.86, p<0.05) and P3/P4 (F=7.83, p<0.05). There were no significant effects at F3/F4 in the 452–596 ms time-window. Two-way ANOVAs revealed a significant TNT×LS interaction at P3 both in the 452–596 ms (F=6.39, p<0.05) and the 600–796 ms time-window (F=7.83, p<0.05), and at F4 in the 600–796 ms time-window (F=9.18, p<0.05). In the 452–596 ms time-window, there was a significant main effect of LS at P4 (F=6.95, p<0.05), but there were no significant effects at either P4 or F3 in the 600–796 ms time-window.

Significant two-way interactions were in turn followed up with repeated measures t-tests comparing paired conditions (degrees of freedom are 22 for all tests), which revealed that the mean ERP amplitudes for Learning Think items were significantly different (against p=0.008; Bonferroni-corrected α for six family-wise comparisons) from the other three conditions in both time-windows at P3 (452–596 ms: Learned Think vs. Not Learned Think, t=5.29, p<0.001; Learned Think vs. Learned No-Think, t=4.14, p<0.001; Learned Think vs. Not Learned No-Think, t=5.31, p<0.001; 600–796 ms: Learned Think vs. Not Learned Think, t=4.48, p<0.001; Learned Think vs. Learned No-Think, t=4.00, p<0.001; Learned Think vs. Not Learned No-Think, t=6.20, p<0.001) and in the later time-window at F4 (600–796 ms: Learned Think vs. Not Learned Think, t=3.97, p<0.001; Learned Think vs. Learned No-Think, t=3.77, p<0.001; Learned Think vs. Not Learned No-Think; t=4.24, p<0.001). None of the other conditions was significantly different from each other at P3 in the 452–596 ms time-window (although the difference between Learned No-Think and Not Learned No-Think conditions neared significance, t=2.83, p<0.01) or at F4 in the 600–796 ms time-window. The Learned No-Think and the Not Learned No-Think conditions did, however, become significantly different at P3 in the 600–796 ms time-window (t=4.02, p<0.001).

In summary, in the later (452 to 1000 ms) time-window, the main finding was that the Think versus No-Think variable interacted with the Learned versus Not Learned variable in modulating the ERPs. The interaction was due to a significantly larger left parietal positivity for the Learned Think condition than the other three conditions between 452 and 800 ms post-stimulus, with a later onset (around 600 ms post-stimulus) polarity reversal on the opposite side of the scalp at right frontal sites. There was, additionally, some evidence of increased left parietal positivity in the Learned No-Think condition compared with the Not Learned No-Think condition in the later part of the time-window.
3. Discussion

The principal results revealed two significant ERP modulations that seem, respectively, to reflect the strategic processing involved in voluntarily controlling recollection (an earlier ERP effect) and the effect this strategic processing has on actual recollection or avoidance of recollection of a stored item-specific memory (a later ERP effect). These modulations were experimentally, topographically, and temporally separable. The nature of the later ERP modulation is consistent with the notion that item-specific recollection of recollectable information can be voluntarily avoided: the left parietal episodic memory effect, which indexes conscious recollection (e.g., Rugg et al., 1996), was observed when participants were trying to recollect learned items, but virtually abolished when they were trying to avoid recollection of learned items.

Anderson et al. (2004) previously found that instructing participants to avoid recollection of previously studied material produced a reduced hemodynamic response in the hippocampus and other recollection-related brain areas compared with instructing participants to recollect the material, a finding interpreted as neural evidence of voluntary avoidance of conscious recollection, at the time such avoidance occurred. However, Anderson et al.’s (2004) fMRI design did not permit for a distinction between the neural correlates of the strategy of recalling or avoiding recollection of the items, and the neural correlates of item-specific recollection versus avoidance of recollection. It also did not permit assessment, at the brain level, of whether instructions to avoid recollection simply reduced conscious recollection or whether conscious recollection was largely eliminated.

The current experiment employed ERPs, which have a much higher time resolution than fMRI, and we separated the ERPs on the basis of learning status within the Think and No-Think conditions, both of which allowed us to address these shortcomings. Furthermore, the current experiment did not show above-baseline subsequent forgetting for No-Think items in the final cued recall test, in common with a number of prior behavioral reports (Bulevich et al., in press; Hertel and Gerstle, 2003; Hertel and Calcatera, 2005), and we restricted our analysis of ERPs during the Think/No-Think phase to items successfully learned at study and successfully recalled in the final cued recall test, and items not successfully learned at study and not successfully recalled in the final cued recalled test. Thus, we could be confident that evidence regarding the ERP correlates of control over recollection during the Think/No-Think phase was not complicated by ERP differences relating to subsequent forgetting between the Think and No-Think conditions, or by differences in item numbers between those conditions. Most notably, for items in the Learned No-Think condition, we could be confident that the relevant response was available in memory because it was subsequently successfully recalled.

3.1. Strategy-related ERP effects

In the 200 to 300 ms time-window, there was a significant ERP effect of the Think versus No-Think instructions which was independent of the learning status of the items. This effect showed a crossover interaction with the anterior–posterior dimension, whereby the ERP amplitudes for items in the Think conditions were bilaterally more positive than the ERP amplitudes for items in the No-Think conditions at fronto-polar and frontal sites, whereas there was a corresponding polarity reversal at parietal and occipital sites, with more negative ERPs bilaterally for Think items than for No-Think items.

Although such a polarity reversal could reflect activity at the two ends of one common dipolar field, the timing and topography of these effects highly resemble two ERP correlates of visual selective attention (e.g., Michie et al., 1999; Potts, 2004; Smid et al., 1999), which have been found to be dissociable because they are sensitive to different functional manipulations (Smid et al., 1999) and can differ in onset latency (Kenemans et al., 1993). More specifically, we suggest that our findings reflect two separate effects, the frontal selection positivity and the posterior selection negativity, both typically found in tasks in which attentional selection is done on the basis of visual features, including color (Aine and Harter, 1986; Harter and Aine, 1984; Kenemans et al., 1993; Michie et al., 1999; Potts, 2004; Smid et al., 1999). The frontal selection positivity (e.g., Kenemans et al., 1993) is characterized by an enhanced positivity for selected compared to ignored stimuli maximal over prefrontal sites between around 120 and 300 ms after stimulus presentation, and the posterior selection negativity (e.g., Harter and Aine, 1984) consists of an enhanced negativity for selected stimuli, also occurring between 120 and 300 ms post-stimulus, but maximal at tempororo-occipital sites. The posterior selection negativity is thought to reflect stimulus-specific perceptual selection, whereas the frontal selection positivity is thought to be more sensitive to task demands, perhaps enabling coupling of relevant stimuli to relevant responses (Allport, 1987).

In the current experiment, participants were cued as to whether they should recall or avoid recollection of an associate by the color of the cue-word (as in Anderson et al., 2004). A useful strategy in this task could be to selectively attend to words displayed in the Think color to enable further retrieval processing, while trying to limit attentional processing of words displayed in the No-Think color in order to prevent further retrieval operations.

Although the early ERP findings may reflect such specific attentional selection mechanisms, our interpretation is tentative because we did not dissociate the early frontal and posterior ERP effects in the current experiment. A general interpretation that can be argued more forcefully, however, is that this learning-independent Think versus No-Think difference reflects early strategic processing. If one accepts the argument that conscious recollection can be strategically controlled, it is plausible to suppose that the control mechanism responsible may often act before conscious recollection. The current data suggest that selective strategic processing already occurred at a very early stage, and this strategic processing may have in turn resulted in selective recollection as indicated by the item-specific ERP effects occurring later.

3.2. Item-specific recollection-related ERP effects

From around 500 to 800 ms post-stimulus there was an interaction between the Think versus No-Think and Learned
versus Not Learned variables, such that the Learned Think condition elicited a significantly larger left parietal positivity than did the Learned No-Think, Not Learned Think, and Not Learned No-Think conditions. This effect also showed a polarity reversal on the opposite side of the scalp at right frontal sites, but it emerged earlier and was more reliable at left parietal sites than at right frontal sites, which suggests that it reflects the activity of two independent generators, rather than activity at the two ends of one common dipolar field. A right frontal negativity associated with a left parietal positivity during memory retrieval has been described previously (e.g., West et al., 2001), although the functional significance of the frontal effect is still unclear.

The enhanced left parietal positivity that we describe for Learned Think items is thought to index conscious recollection (e.g., Paller and Kutas, 1992; Rugg et al., 1996; Wilding and Rugg, 1996). In associative recall tasks in which participants are instructed to recall all associates, the standard finding is that only recognized retrieval cues for which associative recall is successful evoke this left parietal episodic memory effect (Rugg et al., 1996). Our findings therefore suggest that conscious recollection occurred to a significantly larger extent in the Learned Think condition than in the Learned No-Think, Not Learned Think, and Not Learned No-Think conditions.

Because the Learned Think and Learned No-Think ERP conditions in our analysis only contained items successfully learned as well as correctly recalled in the final cued recall test, and because the No-Think instructions did not produce significant subsequent forgetting, interpretation of the ERP differences between these conditions is not complicated by differences in processes that lead to subsequent involuntary forgetting, or by the differences in trial numbers that would result from such differential subsequent forgetting. Instead, the amplitude reduction in the left parietal episodic memory effect for the Learned No-Think condition compared to the Learned Think condition must be due to voluntary processes limiting conscious recollection at the time of the Think/No-Think phase itself.

Amplitudes of ERPs for Learned No-Think items in the late time-window were not only significantly lower than those for Learned Think items at left parietal sites; they were also not significantly different from the ERPs for Not Learned Think items. This finding suggests that recollection of Learned No-Think items was limited in an impressive way: there was no significant ERP difference between learned items that participants were trying not to recall, and items that participants were trying to recall, but could not because those items had not been previously learned.

Two additional features of the ERPs in the late time-window deserve brief comment. First, there was a small but significant increase in left parietal positivity for Learned No-Think items compared with Not Learned No-Think items during the latter part of the time-window, which might indicate that some episodic recollection of Learned No-Think items occurred, although to a much smaller extent than for Learned Think items. Second, there was a trend towards slightly greater left parietal positivity for Not Learned Think items compared with Not Learned No-Think items. That trend suggests that the late left parietal positivity, while primarily reflecting item-specific recollection, may also be somewhat sensitive to retrieval attempts, even when those attempts are unsuccessful.

3.3. Relationship to prior findings, implications, and caveats

Our results converge with ERP results from target/non-target paradigms, which suggest that the left parietal episodic memory effect for previously studied items can be reduced or abolished when recollection is not needed to perform the task (e.g., Dywan et al., 1998, 2001, 2002; Dzulkifli and Wilding, 2005; Herron and Rugg, 2003a, 2003b; Herron and Wilding, 2005; Wilding et al., 2005). However, as previously reviewed in Section 1.2, the target/non-target paradigm cannot distinguish conclusively between mechanisms that operate at encoding or at retrieval because it necessarily involves systematic differences in the encoding phase between items later designated as targets versus non-targets (although see Wilding et al., 2005), and it does not manipulate retrieval strategy directly. In the current experiment, Think and No-Think items were encoded under identical conditions, and retrieval strategy was manipulated directly during the Think/No-Think phase. Thus, ERP differences between the two conditions must be due to differential voluntary retrieval processing.

Although the notion that one can voluntarily avoid episodic recollection is strongly supported by the current ERP findings, there was no greater forgetting of No-Think items in the final cued recall test compared to the Baseline items (which did not appear in the Think/No-Think phase), in common with a number of previous behavioral studies (e.g., Bulevich et al., in press; Hertel and Gerstle, 2003; Hertel and Calcatera, 2005). Those behavioral studies, however, had no objective index of whether participants were limiting recollection of No-Think items during the Think/No-Think phase. Our results, by contrast, provide such an objective index, namely the ERPs for Learned No-Think items, and thereby show much more conclusively than those prior studies that voluntarily avoiding recollection does not inevitably lead to the later involuntary forgetting described by Anderson and Green (2001) and Anderson et al. (2004).

The early strategy-related ERP effects in the current data suggest that participants in the current sample were able to selectively process the retrieval cues at a very early stage, possibly through a selective attentional mechanism that enabled them to disengage from further processing of the No-Think cues, thereby limiting recollection without the need to recruit active inhibition. The failures to find a later memory impairment in the No-Think condition in the prior behavioral experiments may also have occurred because participants chose to engage similar disengagement strategies. Thus, our results suggest that later forgetting may be more likely to occur when participants experience a particular difficulty in voluntarily avoiding recollection, as has been suggested previously (e.g., Anderson et al., 2004). Under the latter circumstances, the ERP correlates of strategies for avoiding recollection, and of avoiding recollection of specific items, may change in interesting ways. Below, we pursue this notion further in relation to the emotional valence of the stimulus material.
We used the standard version of the Think/No-Think paradigm, in which the strategy that participants should use to avoid recollection is not specified by the experimenter (e.g., Anderson and Green, 2001; Anderson et al., 2004). These previous published articles also did not report participants’ subjective estimates of success in avoiding recollection or participants’ subjective reports of the strategies they had used to avoid recollection. We followed those prior articles in not obtaining any such self-report measures in the current experiment, in part because we believed that the value of such self-reports would be highly limited due to demand characteristics. For example, it was strongly emphasized to participants that they should try as hard as possible to avoid recollection of No-Think associates, and any individual differences in self-reported success might well be due to individual differences in the extent to which the participant is trying to “please the experimenter”.

It does, nevertheless, seem that a crucial variable in determining whether voluntary avoidance of recollection will lead to later involuntary forgetting may be the type of strategy used to avoid recollection and that this strategy may need to be experimentally controlled in future studies if researchers want to successfully elicit forgetting effects on later recall tests (see Hertel and Calcaterra, 2005). Our identification of ERP effects relating to a Think/No-Think strategy may, in future studies, assist in distinguishing between different strategies that have different consequences in terms of later forgetting. ERP measurements, unlike self-reports, are beyond the influence of demand characteristics and therefore more likely to truly reflect the participants’ actual strategies and actual success in avoiding recollection than are the participants’ self-reports. Therefore, we believe a more fruitful direction for future research is to combine instructional manipulations of strategy with ERP or other brain activity measurements.

Our results suggest that people can indeed voluntarily avoid thinking of unwanted memories, but our results apply only to unwanted memories of a neutral emotional nature. Such avoidance might occur in everyday situations when a neutral memory is distracting us from a current goal. It remains to be established to what extent it is also possible to voluntarily avoid retrieval of emotionally charged memories. Recent work contrasting neutral and negative materials in a Think/No-Think task has found greater later forgetting of No-Think items when the material was negative compared to neutral (Depue et al., 2006). However, it is as yet unclear how this greater involuntary forgetting as seen on the final test relates to the ability to voluntarily avoid thinking of negative memories during the Think/No-Think phase. Anderson et al. (2004) have suggested that people are initially less able to voluntarily avoid thinking of No-Think items that later become forgotten because the memories that are the most intrusive may trigger greater executive control to override retrieval, which would increase later forgetting. Emotional, and particularly negative, No-Thinks may be more intrusive and thus more subject to later forgetting.

Elucidating this issue requires the measurement of brain activity during the Think/No-Think phase itself, at the time that avoidance of recollection actually occurs, as was done in the current investigation. Our results imply that it would be of great interest in future research to investigate the ERP correlates of voluntary avoidance of recollection for both neutral and emotionally charged information and simultaneously to manipulate strategies for voluntarily avoiding recollection (as previously asserted).

Pending such investigations, though, the clinical and therapeutic implication of the current ERP data is that people are indeed able to voluntarily avoid recollection of uncollectable material, as demonstrated by their brain activity, but that this avoidance of recollection does not necessarily have consequences in terms of later forgetting. Therefore, attempts to treat disorders involving persistent negative memories, such as depression or post-traumatic stress disorder, by inducing patients to avoid retrieving the relevant memories, might meet with success in accomplishing such avoidance during therapy, but might not necessarily succeed in making those memories inaccessible in the long term.

3.4. Summary and conclusion

The current study addressed the issue of whether people are truly able to voluntarily avoid recollecting unwanted, but recollectable, memories. This question is difficult to answer with behavioral or subjective report measures alone. By investigating the neural correlates of conscious recollection during attempts to recollect versus avoid recollecting learned versus not learned information, our research provides a direct answer to this question by showing that such voluntary avoidance of recollection is possible.

The question that we addressed is logically independent of the further question of whether, and if so how, successful voluntary avoidance of recollection leads to later memory impairment, as found in research by Anderson and Green (2001) and Anderson et al. (2004), and indeed we did not find such later memory impairment, in common with a number of previous behavioral studies (e.g., Bulevich et al., in press; Hertel and Gentile, 2003; Hertel and Calcaterra, 2005). Those previous behavioral studies, however, had no objective indices of whether participants were truly avoiding recollection. Regarding this further question, therefore, our results do have the additional implication that successful voluntary avoidance of recollection, as indicated by an objective ERP measure, does not necessitate subsequent forgetting.

The results demonstrate an electrophysiological dissociation between ERP correlates of task-related strategic processes and the ERP correlate of item-specific conscious recollection versus avoidance of recollection. The timing and topography of the early task-related effect suggest that it may reflect two dissociable attentional selection mechanisms (the frontal selection positivity and the posterior selection negativity) which can enable people to avoid recollection without necessitating subsequent forgetting. The reduction in the amplitude of the later left parietal episodic memory effect when participants were attempting to avoid recollection provides complementary evidence to Anderson et al.’s (2004) fMRI results in suggesting that conscious recollection can indeed be strategically avoided, a notion that has been previously contended (e.g., Wegner, 1994). Our findings significantly extend the fMRI results (1) by separating the brain activity correlates of a strategy of avoiding recollection
from the brain correlates of actual item-specific avoidance of recollection; and (2) by showing that item-specific avoidance of recollection was successful to the point where there was little neural evidence of recollection for items that participants had previously learned but were trying to avoid recollecting, compared to items that participants had previously failed to learn but were trying to recollect. The results converge with ERP research using target/non-target recognition tasks in suggesting that the left parietal episodic memory effect is sensitive to strategic processing (Dywan et al., 1998, 2001, 2002; Dzulkifi and Wilding, 2005; Herron and Rugg, 2003a, 2003b; Herron and Wilding, 2005; Wilding et al., 2005). However, in the present study we demonstrated a much more direct link between voluntary control over recollection and the left parietal episodic memory effect by showing unambiguously that the effect is far from automatically generated to materials that are demonstrably recollectable (as indicated by successful recall of those items on a later recall test) and by using a procedure in which all items were initially encoded under identical conditions.

In conclusion, the results demonstrate how an ERP measure of episodic recollection can go well beyond what behavioral or subjective report measures can tell us. In both the Learned Think and Learned No-Think conditions, behavioral measures showed us that the participants had learned the response words and were able to remember them again in a final cued recall test. However, the ERP data show the difference between having learned something and thinking about it, and having learned something but not wanting to think about it right now.

4. Experimental procedures

4.1. Participants

A total of 31 university students participated. The data from four participants were excluded due to the lack of sufficient trial numbers in the Not Learned conditions, and the data of a further four were not analyzed due to excessive eye-blink artefacts. The final sample consisted of 23 right-handed participants of which 7 were male (mean age 24, range 18–35). All were either native English speakers or studying a university course taught in English and had normal or corrected-to-normal vision, including normal color vision. The study was approved by the Goldsmiths College Psychology Department Ethics Committee, meaning that it was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All participants gave their informed consent prior to their inclusion in the study and received either a small payment or course credits.

4.2. Materials and procedure

The stimuli consisted of 60 weakly related or unrelated word pairs, 40 of which were used in the Anderson et al. (2004) study. A further 20 word pairs were developed, which had similar degree of intra-pair relatedness as the Anderson et al. (2004) word pairs (i.e., weakly related or unrelated) according to the Moss and Older (1996) word association norms. Participants initially studied all 60 pairs, of which 20 pairs were assigned to the Think condition, 20 to the No-Think condition, and 20 the Baseline condition, respectively (see below for assignment details). Think and No-Think pairs were then included in the subsequent Think/No-Think phase, in which participants were cued with the first word of each pair and asked recall of Think associates and avoid recall of No-Think associates. Pairs in the Baseline condition were not included in the Think/No-Think phase, but formed a behavioral baseline condition for the later final cued recall test (see Anderson and Green, 2001; Anderson et al., 2004), in which all 60 initially studied pairs were tested. ERPs reported here are from the Think/No-Think phase.

Based on the results of the initial cued recall test at the end of the study phase, initially learned and not learned pairs were randomly assigned to either Baseline, Think or No-Think conditions in as equal proportions as possible. If a participant’s number of initially learned pairs (e.g., 27), and hence also their number of initially not learned pairs (e.g., 33), was divisible by three, an equal number of learned pairs were randomly assigned to each of the Think, No-Think, and Baseline conditions (e.g., 9 per condition), and an equal number of not learned pairs were randomly assigned to each of the Think, No-Think, and Baseline conditions (e.g., 11 per condition). If a participant’s numbers of initially learned and not learned pairs were not divisible by three, pairs were randomly assigned so that there were always an equal number of initially learned and not learned pairs in the Think and No-Think conditions and that the odd-numbered condition was always Baseline. For example, 28 initially learned pairs and 32 initially not learned pairs would mean that the Think and No-Think conditions would contain 9 initially learned pairs each and that the Baseline condition would contain 10 pairs. The Think and No-Think conditions would then contain 11 initially not learned pairs each, and the Baseline condition would contain 10 initially not learned pairs. The reason for this assignment procedure was to assure that, at the level of individual participants, there was no possibility of introducing oddball effects into the ERPs during the Think/No-Think phase due to different proportions of initially learned items across the Think and No-Think conditions.

In summary, each participant always had 20 items total in each condition (Think, No-Think, and Baseline, respectively), and equal numbers of initially Learned and not learned items in the Think and No-Think conditions, with the only possible difference between participants being the relative numbers of initially learned and initially not learned items. These relative numbers reflected the participant’s performance in the initial cued recall test at the end of the study phase (on average, across participants, 55% initially learned, 45% initially not learned; see Section 2.1). These average initial performance percentages produced an average of 11 initially learned items and an average of 9 initially not learned items in both the Think and No-Think conditions. Importantly, to participate in the critical Learned and Not Learned conditions for ERP analysis, Learned items had to satisfy the additional criterion of being successfully recalled in the final cued recall test, and Not Learned items had to satisfy the additional criterion of not being successfully recalled in the final cued recall test.
The general design of the tasks was adapted from Anderson et al.’s (2004) protocol. Stimuli were presented using E-Prime v1.1 software (Psychology Software tools, Pittsburgh, PA, USA). In the initial learning phase (Phase 1), 60 word pairs were presented in a random order for a duration of 3000 ms each on a computer screen, with 500 ms intervals between words. Using a shorter presentation duration with a larger number of stimulus words than Anderson and Green (2001) and Anderson et al. (2004) ensured that learning accuracy was kept sufficiently low to produce an adequate number of items in the Not Learned conditions in the subsequent Think/No-Think phase. Participants were told that they should try to memorize the word pairs because they would subsequently have their memory tested by being presented with one of the words as a cue and would have to give the other as their response. This study phase was immediately followed by a test of initial learning, in which participants were given the word previously presented on the left and asked to recall the word previously presented on the right. If participants failed to achieve a minimum of 25% correct responses, the study presentation phase was repeated and their memory tested again in the same manner. No participant required more than three presentations to achieve minimum accuracy.

Immediately after the initial memory test, participants were seated in an adjacent sound- and light-attenuated room facing a display monitor and fitted with an EEG recording cap for gathering data during the Think/No-Think phase. They were given instructions adapted from the Anderson et al. (2004) protocol and told that they would again be presented with the cue-words from the previous memory test, but that this time the task would differ depending on the color in which the word was presented. For half of the participants, a cue-word in yellow signified the Think condition and a cue-word in light blue signified the No-Think condition, and for the other half, yellow signified the No-Think condition and light blue signified the Think condition. Each trial began with a 500 ms fixation cross, followed by the cue-word displayed for 3000 ms in the center of the screen, in either yellow or light blue. After 3000 ms, a green star appeared below the word and this display lasted for another 1000 ms, until it was replaced by a black screen, also with a duration of 1000 ms. After every four trials, there was a 3000 ms blink-pause.

To ensure that ERPs were not differentially affected by activity related to the preparation and execution of a verbal response, verbal responding, prompted by the green star cue, was required in all conditions. On Think trials, participants were instructed to immediately retrieve the associated response for each cue and silently keep it in mind for 3000 ms until the green star appeared, when they should say the response aloud. The verbal responding was delayed in order to avoid motor-related electrical artefacts in the ERPs. If they were not able to remember the response, they should say “think” when the green star appeared. On No-Think trials, participants were told that they would still have to read the cue-word and pay full attention to it, but that they were to avoid thinking of its associate response completely, never allowing it to enter consciousness. When the green star appeared in the No-Think condition, participants were to respond “no”, regardless of the learning status of the word.

Half of the cues appeared in each condition, and each list of cues was displayed in a random order. Lists were repeated 16 times, in line with Anderson et al. (2004). The trials were divided into four blocks of four lists each, with short breaks between blocks. ERPs were obtained by averaging across these 16 list repetitions in order to obtain an adequate signal-to-noise ratio.

Following the Think/No-Think phase, a final cued recall test was conducted, in which participants were given all 60 originally studied cue-words presented in white (each cue being presented once, and with the cues being presented in a random order) and told to ignore previous instructions and give the associated response to each cue. If they failed to respond within 5 s, the computer moved onto the next cue-word. This final recall test included the Baseline items, which had been studied at the beginning of the experiment, but were not included in the intervening Think/No-Think phase.

4.3. EEG recording and data processing

EEG was recorded from 30 Ag/AgCl scalp electrodes embedded in a Neuroscan Easycap, with two additional sets of linked electrodes measuring the electro-oculogram (EOG), and referenced to linked mastoids. The vertical EOG was measured from electrodes placed above and below the left eye (referenced to each other), and the horizontal EOG was recorded from electrodes embedded in the cap adjacent to the outer canthus of the left and the right eye (also referenced to each other). Midline electrode locations were Fz, Fcz, Cz, Cpz, Pz, and Oz, and left and right hemisphere sites were Fp1/Fp2, F3/ F4, F7/F8, Fc3/Fc4, Ft7/Ft8, C3/C4, T7/T8, Cp3/Cp4, Tp7/Tp8, P3/ P4, P7/P8, and O1/O2. Signals were amplified with a bandwidth of 0.1 to 100 Hz using a Neuroscan (El Paso, Texas, USA) Synamp DC-coupled amplifier, with a gain of 500 and a sampling rate of 250 Hz. Electrode-scalp impedances were kept below 5 kΩ. Acquired data were analyzed using Neuroscan Edit software, except for the topographic plotting which was done using EEGLAB (Delorme and Makeig, 2004). The continuous EEG data were filtered digitally (2-pass Butterworth with zero phase shift) with band-pass of 0.3–30 Hz and re-referenced to an average reference. Although using an average reference is typically only recommended for recordings using 64 or more channels (Dien, 1998; Junghofer et al., 1999), the current dataset was re-referenced to facilitate the detection of lateralized effects (in particular the left parietal episodic memory effect). Analysis of the same data using a linked mastoid reference (not presented) showed highly similar early and late experimental effects to those reported here, although the posterior effects were more centrally distributed across occipital and parietal regions and less visible over temporal regions, due to their spatial proximity to the mastoid reference sites.

Epochs were created off-line beginning 100 ms prior to stimulus onset and lasting until 1500 ms post-stimulus. Epochs containing artefacts with a base-to-peak amplitude exceeding $112 \mu V$ on any channel or $90 \mu V$ on HEOG were excluded, and epochs were also inspected manually, with any further epochs that were deemed to contain artefacts being rejected. The average rejection rate was 17% (range 7–32%).
After artefact rejection, the mean numbers of trials contributing to the ERPs were 139 for Learned Think items, 97 for Not Learned Think items, 133 for Learned No-Think items, and 101 for Not Learned No-Think items. All participants who were included in the analysis had more than 16 artefact-free trials in each condition. The lower numbers of accepted trials for Not Learned compared with Learned items reflect the mean level of successful versus unsuccessful learning in the study phase (on average, 55% initially learned, 45% initially not learned; see Sections 2.1 and 4.2).

4.4 ERP statistical analysis

4.4.1 Partial least squares

Initial data analysis was conducted using mean-centered (equivalent to the Helmert matrix version described in Lobaugh et al., 2001) spatiotemporal Partial Least Squares (PLS), a multivariate statistical technique that allows examination of distributed patterns of spatial and temporal dependencies in the ERP data (Duzel et al., 2003, 2005; Lobaugh et al., 2001; McIntosh et al., 1996; McIntosh and Lobaugh, 2004). PLS computes the “cross-block” covariance between a matrix of dependent measures (the spatiotemporal ERP distribution) and a set of exogenous measures, in this case orthogonal contrast vectors representing the experimental conditions, thereby constraining the solution to covariance attributable to the experimental manipulation (McIntosh and Lobaugh, 2004). The output covariance maps (one per contrast vector) are then combined into a matrix and decomposed with singular value decomposition (SVD). The SVD extracts as many mutually orthogonal latent variables (LVs) as there are degrees of freedom in the experimental design contrast.

Each LV contains three types of information: (1) a design salience (singular profile) that represents a particular pattern of contrasts between experimental conditions; (2) electrode saliences (singular image), which identify the electrodes that most strongly covary at a particular point in time with the experimental contrast expressed in the design salience; and (3) singular values, which are used to estimate the amount of cross-block covariance accounted for by the LV. A permutation test is performed to assess the statistical significance of each LV, whereby each participant’s data are randomly reassigned without replacement to different experimental conditions and the PLS recomputed. After 500 such randomizations, the number of times the singular value of the permuted PLS exceeded the singular value of the observed PLS is computed, giving an exact significance value for the observed LV. The standard errors of the electrode saliences are estimated through bootstrap sampling, using sampling with replacement and keeping the experimental conditions fixed for all observations, and the PLS is then recalculated for each bootstrap sample. If the value of an electrode salience is greatly dependent on which observation is in the sample, it is less stable than an observation that remains similar regardless of the sample chosen (McIntosh and Lobaugh, 2004). The ratio of the electrode salience to the bootstrap standard error is approximately equivalent to a z score if the bootstrap distribution is normal (McIntosh and Lobaugh, 2004).

The reasons for using PLS for initial analysis are several. First, PLS requires no initial assumptions regarding temporal or spatial properties of the experimental effects, which is desirable for the current analysis because no ERP effects associated with the Think/No-Think task have been previously described. Second, it minimizes the subjective aspects of selecting time-windows and electrode locations on which to perform analysis. These decisions are often based on post hoc considerations in traditional univariate analysis of exploratory ERP data, which opens the possibility of manipulation of the results of analyses by selecting data. Third, because PLS is a multivariate technique, it is more powerful than univariate techniques when analyzing correlated brain data (see McIntosh et al., 2004). Fourth, the number of statistical tests is minimized because the assessment is applied at the level of the full spatiotemporal pattern, only testing the significance of the extracted latent variables, which do not exceed the number of degrees of freedom of the design. Fifth, the bootstrap ratios determine the reliability of the experimental effects at each electrode and time-point and thus no corrections for multiple comparisons are necessary because no further statistical tests are performed as part of the PLS. In summary, we used PLS as an initial exploratory tool and restricted traditional univariate analysis to ERP effects first identified as significant and reliable by PLS. Matlab code to perform PLS analysis is available at (http://www.rotman-baycrest.on.ca/pls).

4.4.2 Further univariate analysis

PLS with singular value decomposition can extract LVs that are combinations of main effects as well as combinations of main effects and interactions when applied to a factorial design. We therefore performed follow-up factorial univariate analyses at four sites that reliably showed the effects expressed by the significant latent variables in four time-windows that best captured the effects. Two frontal (F3, left frontal; F4, right frontal) and two parietal (P3, left parietal; P4, right parietal) sites were selected and ANOVAs with Instruction (Think/No-Think; TNT), Learning (Learned/Not Learned; LS), Hemisphere (Left/Right; HM), and Anterior–Posterior (Anterior/Posterior; ANT) as factors were conducted for four time-windows, 200–296 ms, 300–396 ms, 452–596 ms, and 600–796 ms. Significant effects in the four-way ANOVAs involving the experimental variables of interest were followed up with further three-way ANOVAs, two-way ANOVAs, or simple main-effects analyses as appropriate. Significant interaction effects in the 2-way ANOVAs were followed up with simple comparisons if required.

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