Event-related Potential Evidence that Automatic Recollection Can Be Voluntarily Avoided

Zara M. Bergström[1,2], Jan de Fockert[1], and Alan Richardson-Klavehn[2]

Abstract

■ Voluntary control processes can be recruited to facilitate recollection in situations where a retrieval cue fails to automatically bring to mind a desired episodic memory. We investigated whether voluntary control processes can also stop recollection of unwanted memories that would otherwise have been automatically recollected. Participants were trained on cue–associate word-pairs, then repeatedly presented with the cue and asked to either recollect or avoid recollecting the associate, while having the event-related potential (ERP) correlate of conscious recollection measured. Halfway through the phase, some cues switched instructions so that participants had to start avoiding recall of associates they had previously repeatedly recalled, and vice versa. ERPs during recollection avoidance showed a significantly reduced positivity in the correlate of conscious recollection, and switching instructions reversed the ERP effect even for items that had been previously repeatedly recalled, suggesting that voluntary control processes can override highly practiced, automatic recollection. Avoiding recollection of particularly prepotent memories was associated with an additional, earlier ERP negativity that was separable from the later voluntary modulation of conscious recollection. The findings have implications for theories of memory retrieval by highlighting the involvement of voluntary attentional processes in controlling conscious recollection. ■

INTRODUCTION

In memory research, a distinction has been made between incidental recollection, where a retrieval cue automatically and unintentionally brings to mind an associated episodic memory, and intentional recollection, where a retrieval cue fails to automatically bring a wanted memory to mind, and people have to engage voluntary retrieval strategies to successfully recollect the memory (e.g., Richardson-Klavehn & Gardiner, 1995; Richardson-Klavehn, Gardiner, & Java, 1994). A corresponding voluntary control over recollection has been suggested to operate in situations where, upon encountering a retrieval cue, people wish to *stop* the associated memory from coming to mind. Stopping recollection of an unwanted memory is thought to require the involvement of active, voluntary control processes—*if* recollection is the prepotent, automatic response to a cue, and retrieval therefore has to be actively overridden (Anderson et al., 2004; Levy & Anderson, 2002; Anderson & Green, 2001).

By measuring the brain activity correlates of conscious recollection during memory tasks, a number of studies have provided evidence that people can strategically control recollection (Bergström, Velmans, de Fockert, & Richardson-Klavehn, 2007; Depue, Curran, & Banich, 2007; Fraser, Bridson, & Wilding, 2007; Dzulkifli, Herron, & Wilding, 2006; Dzulkifli & Wilding, 2005; Herron & Wilding, 2005; Wilding, Fraser, & Herron, 2005; Anderson et al., 2004; Herron & Rugg, 2003a, 2003b; Dywan, Segalowitz, & Arsenault, 2002; Dywan, Segalowitz, Webster, Hendry, & Harding, 2001; Dywan, Segalowitz, & Webster, 1998). However, none of the above studies directly addressed to what extent recollection of potentially recollectable materials can be voluntarily avoided when retrieval is the prepotent, automatic response. This issue not only has implications for theories of cognitive control and memory retrieval but also has practical applications for brain activity tests of concealed information (e.g., Farwell & Donchin, 1991), which rely on the assumption that memory-related brain activity should be uncontrollably elicited by retrieval cues related to the concealed information. In the current study, we therefore aimed to determine whether it is possible to voluntarily avoid automatic recollection.

A clear distinction between intentional and incidental recollection dates back to Ebbinghaus (1885/1964; in Mace, 2006). This distinction has been incorporated in more recent interpretations of level-of-processing effects in implicit memory tests (Richardson-Klavehn & Gardiner, 1995; Richardson-Klavehn, Gardiner, et al., 1994; Richardson-Klavehn, Lee, Joubran, & Bjork, 1994) and in models of episodic memory retrieval. Moscovitch (1992) suggested that incidental episodic retrieval relies on automatic cue–trace interactions mediated by the medial-temporal lobe (MTL)/hippocampus. In contrast,

[1]Goldsmiths, University of London, UK, [2]Otto von Guericke University, Magdeburg, Germany

intentional episodic retrieval relies on voluntary control processes mediated by frontal brain regions, that devise and initiate retrieval strategies if the initial retrieval cue is insufficient to elicit automatic recollection, and in doing so, interacts with the MTL/hippocampus to elicit recollection of the desired memory. A large amount of functional neuroimaging literature now supports the idea that frontal areas are involved in strategic aspects of retrieval (see Buckner, 2003, for a review) and that hippocampal activation is more closely related to the actual recollection of an event than the intention to remember an event (Rugg, Fletcher, Frith, Frackowiak, & Dolan, 1997; Schacter, Alpert, Savage, Rauch, & Albert, 1996).

Anderson and Green (2001) introduced the idea that voluntary strategic processes may also be involved in situations where the goal is to *stop* automatic recollection from taking place. In their think/no-think paradigm, participants initially learn a list of cue–response pairs and are then repeatedly presented with the cue, and asked to either recall the associated memory response (the think condition), or to completely prevent the associated response from entering consciousness (the no-think condition). It is assumed that upon processing of the cue, the prepotent response is to automatically retrieve the associate, and to achieve successful avoidance of recollection, automatic retrieval has to be prevented by active control processes (Anderson et al., 2004; Levy & Anderson, 2002; Anderson & Green, 2001). Indirect evidence that prepotent recollection has been voluntarily stopped comes from a surprise final recall test, in which recall of the previously avoided memories is typically impaired compared to a baseline condition which measures simple forgetting over time. It is reasoned that a significant impairment of no-think associates must be a consequence of the involvement of executive control processes in stopping prepotent recollection, as beyond-baseline forgetting of no-think associates should only be found if stopping recollection had required additional, effortful processing. However, the relationship between voluntary avoidance of recall and subsequent beyond-baseline forgetting is not clear cut because it has been suggested that only memories that initially come to mind are subsequently impaired (Depue et al., 2007; Anderson et al., 2004). It is therefore unclear on the basis of the behavioral evidence to what extent prepotent recollection can be successfully avoided at the time that attempted avoidance occurs, and whether intrusive memories can be voluntarily avoided without being subsequently forgotten.

Stronger evidence that recollection can be voluntarily avoided was found in two fMRI studies using the think/no-think task, which reported that hippocampal activity was reduced during no-think trials compared to think trials (Anderson et al., 2004), and that both hippocampal and visual representational activity was reduced during no-think trials compared to baseline levels of activity (Depue et al., 2007), indicating reduced recollection of no-think associates. In addition, both studies showed increased activity for no-think trials in a number of frontal regions that are typically involved in cognitive control, such as the dorsolateral and ventrolateral prefrontal cortex, the fronto-polar cortex, and the ACC, indicating that participants were engaging effortful control processes to avoid recollection. However, neither of the studies directly manipulated or measured the intrusiveness of the memories to-be-avoided, thus only provide indirect evidence that prepotent recollection was voluntarily avoided.

In the ERP domain, researchers have used the ERP correlate of conscious recollection to investigate whether recollection can be strategically controlled. The ERP correlate of conscious recollection is a positive shift of the ERP at centro-parietal regions, typically left-lateralized, maximal approximately 500 to 800 msec after stimulus presentation (Rugg, 1995; Smith, 1993; Paller & Kutas, 1992). The effect is specifically linked to recollection because it is larger if participants, in addition to recognizing previously presented items as old, can also correctly identify their source (Wilding, 2000; Wilding & Rugg, 1996; Wilding, Doyle, & Rugg, 1995), and if the items are associated with a "remember" (contextual recollection) rather than "know" (familiarity) judgment (Düzel, Yonelinas, Mangun, Heinze, & Tulving, 1997; Smith, 1993). Moreover, the effect is absent in neuropsychological patients with impaired recollection due to hippocampal lesions (Düzel, Vargha-Khadem, Heinze, & Mishkin, 2001). Importantly for the current research, in associative cued recall tasks, the effect is only found for recognized old recall cues for which *recall of the associate is successful* (Rugg, Schloerscheidt, Doyle, Cox, & Patching, 1996). Although typically known as the parietal "old/new" effect, we refer to it as the parietal episodic memory (EM) effect (Friedman & Johnson, 2000) because of the strong evidence linking the effect with conscious recollection.

Initial evidence of voluntary control of recollection as indexed by the parietal EM effect has been found in studies using the target/nontarget exclusion paradigm (Fraser et al., 2007; Dzulkifli et al., 2006; Dzulkifli & Wilding, 2005; Herron & Wilding, 2005; Wilding et al., 2005; Herron & Rugg, 2003a, 2003b; Dywan et al., 1998, 2001, 2002). In this paradigm, participants are, during an initial encoding task, presented with two sets of stimuli that differ on some dimension (e.g., by being presented in different temporal or perceptual contexts). This is followed by a modified old/new recognition test, in which only one set of old items is designated as targets requiring one response at test, whereas the other set of old items is designated as nontargets, which together with new items require another response at test. The typical pattern of ERP findings has been that when the probability of correctly recollecting targets is high, the parietal EM effect occurs for targets compared to new words, but not for nontargets 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 parietal EM effect occurs for both targets and nontargets compared to new words.

The interpretation of these findings has been that, when target memory is good, conscious recollection is strategically controlled to occur only in response to targets and not to nontargets (Herron & Rugg, 2003b). This strategy might be efficient when target recollection is likely because participants could successfully perform the task by attempting to selectively recollect episodic information associated with the targets 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, as success or failure of target source recall would be less informative, thus requiring recollection of both target and nontarget episodes for successful task performance. However, the target/nontarget paradigm does not explicitly ask participants to control recollection, and thus, only provides indirect evidence regarding such strategic control. In addition, there is no indication in the target/nontarget task that recollection is the prepotent response during test, so it provides little information regarding the current issue of the extent to which voluntary avoidance of automatic recollection is possible.

More direct ERP evidence of voluntary avoidance of recollection was provided by a recent study using a modified version of the think/no-think procedure, which separated ERPs in the think/no-think phase as a function whether the paired associates were learned or not learned during the previous study phase (Bergström et al., 2007). Comparing ERPs when participants were instructed to recollect versus avoid recollection of learned versus not learned information permitted an examination of how successful participants were at controlling recollection, as indicated by differences in the parietal EM effect. Instructing participants to recollect learned memories elicited a larger parietal EM effect than did instructing participants to avoid recollection of learned memories, and moreover, there was no difference in the parietal EM effect for learned items for which participants were avoiding recollection and for items that participants had failed to learn but were trying to recollect. The results demonstrated that recollection avoidance was successful to the point where there was little neural evidence of recollection for learned no-think items, providing strong evidence that conscious recollection of recollectable information was successfully avoided on an item-specific basis. However, similarly to the think/no-think fMRI studies, although recollection is typically assumed to be the prepotent response during the think/no-think phase, this was not directly verified in the above study, thus whether or not the results reflected voluntary avoidance of automatic recollection was not conclusively determined.

An alternative explanation for why recollection could be successfully avoided in both the target/nontarget and the think/no-think studies is that perhaps the default state during both tasks is to *not* recollect, that is, that the cues fail to elicit automatic recollection. According to this account, the memories that participants are asked to recall require the involvement of intentional control processes to achieve successful retrieval, and successfully avoiding recall requires no voluntary control. This explanation fits with the large body of previous research on voluntary retrieval strategies (see e.g., Buckner, 2003; Rugg & Wilding, 2000). Identifying the locus of strategic processes in the control of recollection—whether they act to stop retrieval of unwanted memories or to achieve successful retrieval of wanted memories—is not possible on the basis of the parietal EM effect alone because this effect is associated with the actual recollection of an event, irrespective of whether recollection is intentional or incidental (Curran, 1999).

In the present study, we tested directly whether automatic recollection can be voluntarily avoided, and manipulated the strength and flexibility of voluntary control over recollection by requiring participants to switch within-items between think and no-think strategies, while measuring the ERP correlate of conscious recollection. We first trained participants on a list of word-pairs, tested their learning in an initial learning test, and then repeatedly presented the first member of the pair with standard think/no-think instructions to either think of, or avoid thinking of, the associate word, depending on the color of the cue word (Bergström et al., 2007; Anderson et al., 2004). Critically, following the first half of the cue presentations, participants were told that half of the cues would swap color for the rest of the phase, but that the other half of the cues would remain in the same color as during the first half of the presentations. They were told that the instructions associated with each color would remain the same so that they would now be required to avoid recall of some associate words that they had previously been repeatedly recalling, and to recall some associate words for which they had previously avoided recall. It was reasoned that recalling some associates repeatedly (eight times) in response to the cue during the first half of presentations would ensure that recollection of those associates was the prepotent, automatic response when the cues swapped instructions (see Wheeler & Buckner, 2003 for a similar manipulation to achieve automatic recollection). Testing whether the parietal EM effect was significantly reduced in the second half of presentations for items that had swapped from having been repeatedly recalled to requiring avoidance of recollection would thus allow the assessment of whether prepotent recollection could be avoided. In addition, participants rated their perceived difficulty and success at avoiding recollection throughout the think/no-think phase, to verify that they were, indeed, employing effortful control to avoid recollection.

To ensure that differences in ERPs were due to voluntary processes at the time of recollection or recollection avoidance, as opposed to different proportions of involuntary forgetting between the think and no-think conditions, cues were only included in the main ERP analysis if participants could recall the associate word both in the initial learning test and in a surprise final recall test following the think/no-think phase. This criterion meant that we could be confident that for all cues included in the ERP conditions, participants could recollect the associate should they try to do so, and therefore, our predicted ERP differences in the parietal EM effect could be ascribed to voluntary processes at the time of recollection avoidance. The current study thus addressed the question of whether people are able to voluntarily avoid conscious recollection of demonstrably recollectable information. This question is logically independent of the further question of whether, and if so how, successful voluntary avoidance of recollection leads to later memory impairment, as investigated in previous research (e.g., Depue et al., 2007; Depue, Banich, & Curran, 2006; Anderson et al., 2004; Anderson & Green, 2001). In fact, voluntary avoidance of recollection is better investigated in situations *without* subsequent enhanced forgetting of the avoided information, because it means that the issue can be examined unconfounded by ERP differences between conditions in terms of processes related to differential later forgetting.[1] Thus, we emphasize that we make no claim in the current article to demonstrate ERP differences related to processes causative of later forgetting.

Successful voluntary avoidance of episodic recollection predicts a reduction in the positivity of the parietal EM effect for no-think items compared with think items. If participants are successful at controlling recollection during the first half of the think/no-think presentations, the positivity of the left parietal EM effect should be reduced for the two ERP conditions that have no-think as their first half instruction compared to the two ERP conditions that have think as their first half instruction. During the second half of the presentations, if participants fail to switch recall strategy for items that swap between the think and no-think conditions, we should observe the same pattern of amplitudes in the parietal EM effect on the basis of first half instructions. If participants can successfully switch recall strategy for items that swap think/no-think conditions, the ERPs should separate on the basis of second half instructions, with the positivity of the parietal EM effect reduced for the two ERP conditions that have no-think as their second half instruction compared to the two ERP conditions that have think as their second half instruction. Such a finding would indicate that voluntary control over recollection is strong and flexible. In particular, finding a significantly reduced positivity of the parietal EM effect for items that had swapped from think to no-think instructions would suggest that automatic recollection of prepotent memories can be voluntarily avoided.

METHODS

Participants

Four participants were replaced due to excessive EEG artifacts. The final sample consisted of 24 (7 men) right-handed, native English speakers (mean age = 22 years, range = 18–31 years) with normal or corrected-to-normal vision, including normal color vision. The study was approved by the Goldsmiths College Psychology Department Ethics Committee. All participants gave informed consent prior to their inclusion in the study, and received either a small payment or course credits.

Materials

The stimuli consisted of 48 weakly related word-pairs, of which 8 were fillers. The pairs were previously used in Bergström et al. (2007) and Anderson et al. (2004). The assignment of word-pairs to each of the four experimental conditions (10 pairs in each) was counterbalanced across participants. In our adaptation of the task, we did not include a behavioral baseline condition because the aim of the experiment was to investigate voluntary control over recollection of recollectable material, for which measuring subsequent forgetting compared to baseline is not required.

Procedure

Stimulus presentation was done using E-Prime v1.1 software (Psychology Software Tools, Pittsburgh, PA). At arrival, participants were fitted with an EEG recording cap for gathering the ERP data and were seated in an electrically shielded and sound- and light-attenuated Faraday cage, facing a shielded display monitor. In the initial learning phase (Phase 1), 48 word-pairs were presented in a random order on a computer screen (5000 msec duration, 1000 msec intertrial interval), and participants were asked to memorize the word-pairs for a later test. Immediately following study, participants undertook a test of initial learning by being given one of the words as a cue and were asked to recall the associate word. If less than 25% correct, the study presentation phase was repeated and memory was tested again in the same manner (no one required more than two presentations to achieve minimum accuracy).

Next, participants received instructions for the think/no-think phase, which were adapted from the Anderson et al. (2004) protocol and identical to those used in Bergström et al. (2007). They were 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.

The color representing each condition was counterbalanced across participants. After a 2000-msec fixation cross, the cue word was displayed for 2000 msec in the center of the screen, in either yellow or light blue. After 2000 msec, a green star appeared below the word and this display lasted for another 1000 msec, until it was replaced by a black screen, also with a duration of 1000 msec. Participants were asked to only blink while the green star or the black screen was displayed. To ensure that ERPs were not differentially affected by activity related to the preparation and execution of a verbal response, verbal responding was required in all conditions (delayed to prevent motor-related electrical artifacts affecting the ERPs). On think trials, participants were instructed to immediately recollect the associated response for each cue, and silently keep it in mind for 2000 msec until the green star appeared, when they should say the response aloud. 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 always respond "no." For initially learned items, participants' accuracy at verbalizing the think responses and responding "no" to no-think cues was at ceiling, and the few trials in which an incorrect response was given were excluded from the ERP conditions.

After a practice think/no-think phase on eight filler items, the experimental think/no-think phase was administered, in which 20 cues appeared in each think or no-think color, intermixed into a list of 40 cues displayed in a random order. Lists were repeatedly presented, divided into four blocks of four lists each with short breaks between blocks (16 list presentations in total). After each four-list block, participants were asked to rate how difficult they had found it to avoiding thinking of the no-think associates in that block on a scale between 1 (*extremely easy*) and 7 (*extremely difficult*), and to estimate the percentage of trials on which they had been able to completely prevent the no-think associates from coming to mind.

After the first two blocks (i.e., 8 presentations, half of the total number of presentations), participants were given new instructions informing them that in the following two blocks, the color in which some of the words would be presented would swap, so that some of the words that were presented in yellow during Blocks 1 and 2 would be presented in blue during Blocks 3 and 4, and some words that were presented in blue during Blocks 1 and 2 would be presented in yellow during Blocks 3 and 4, whereas the rest of the words would continue to be presented in the same color in which they were presented previously. The instructions associated with each color remained the same so for cues in the think color, they should still think of the associated word as fast as possible, and for cues in the no-think color, they should still completely avoid thinking of the associated word. It was emphasized that because some words had swapped conditions this could take a bit of extra effort so they should try their best. The task was then continued for another two blocks with four lists each so that each item was presented eight additional times after the new instructions.

Following the think/no-think phase, a final recall test was conducted, with all cue words presented in white for 5 sec (each cue presented once in a random order) and participants were asked to ignore previous instructions and give the associated response to each cue. The purpose of the final recall test was to detect any items that participants may have forgotten during the think/no-think phase and exclude those from the ERP analysis, to ensure that any ERP effects were due to voluntary processing of recollectable information, and not due to different proportions of forgotten items between the conditions. Finally, participants were given a questionnaire (courtesy of Benjamin J. Levy and Michael C. Anderson) which asked them a number of questions regarding the strategies they had used to avoid recollection on no-think trials, and the degree to which they had been following no-think instructions. The questionnaire data were collected with the aim to correlate parietal EM effects with self-reported strategies.

EEG Recording and Data Processing

EEG was recorded using Neuroscan (El Paso, TX) Synamps DC-amplifiers from 30 Ag/AgCl scalp electrodes at standard locations from the extended 10–20 system using a Neuroscan Easycap, with two additional sets of linked electrodes measuring the electrooculogram (VEOG and HEOG), and referenced to the average of mastoids (bandwidth 0.1–100 Hz, gain 500, sampling rate 250 Hz). Electrode scalp impedances were kept below 10 kΩ. Acquired data were analyzed using Neuroscan Edit software, except for the topographic plotting which was done using EEGLAB (Delorme & Makeig, 2004). The continuous EEG data were filtered digitally (0.3–30 Hz, two-pass Butterworth with zero phase shift) and re-referenced to an average reference in line with Bergström et al. (2007). Epochs were created off-line beginning 200 msec prior to stimulus onset and lasting until 1500 msec poststimulus. Epochs containing artifacts with a base to peak amplitude exceeding 112 μV on any channel or 90 μV on HEOG were excluded, and epochs were also inspected manually, with any further epochs that were deemed to contain artifacts being rejected. The average rejection rate was 12.6% (range 4–26%). ERPs were separately averaged across the first half of cue-word repetitions and across the second half of cue-word presentations for the four conditions on the basis of first half think/no-think instructions and second half think/no-think instructions. Cues that received think instructions both in the first and second half of presentations are referred to as T–T, cues that received think instructions in the first half but no-think instructions in the second half of presentations are referred to as T–NT, cues that received no-think instructions in the first half but think instructions in the second half are referred to as NT–T, and cues that received no-think instructions both in the first and second half of presentations are referred to as NT–NT. After artifact rejection, the mean number of trials contributing to the ERPs in the first half was T–T: 48; T–NT: 48; NT–T: 47; and NT–NT: 46; and in the second half was T–T: 50; T–NT: 50; NT–T: 49; and NT–NT: 48. All participants who were included in the analysis had more than 15 artifact-free trials in each condition.

In order to verify that the predicted parietal ERP effects reflected voluntary modulations of item-specific recollection rather than more general task-related differences, a follow-up analysis was performed for a subset of 10 participants by creating ERPs also for items that were neither successfully learned on the initial learning test nor successfully recalled on the final test (in line with Bergström et al., 2007).[2] The ERPs for these not-learned items were compared against the ERPs for the successfully learned items for the same participants. Because the only difference between conditions during the first half of presentations was whether items were presented with first half think or no-think instructions, the ERPs for the first half were collapsed across second half instruction to increase signal-to-noise ratio, into average learned and not learned first half think and no-think conditions (mean trial numbers for the first half: average learned think: 75; average not learned think: 49; average learned no-think: 75; average not learned no-think: 44). ERPs for the second half were, however, computed separately for learned and not learned T–T, T–NT, NT–T, and NT–NT conditions to investigate whether the predicted second half effects were memory-specific (mean trial numbers per condition for the second half: learned ERP conditions: T–T: 41, T–NT: 38, NT–T: 39, NT–NT: 40; not learned ERP conditions: T–T: 22, T–NT: 31, NT–T: 26, NT–NT: 23). Again, all participants who were included in the follow-up analysis had more than 15 artifact-free trials in each condition.

On the basis of prior results (Bergström et al., 2007), it was predicted that the differences in parietal EM positivity between think and no-think trials should be present primarily for learned items and not for not-learned items. Such a result would support the conclusion that the parietal ERP modulations primarily reflected successful recollection or successful avoidance of recollection of specific items rather than generic, task-related processes, as the latter would be expected to be engaged irrespectively of the learning status of the items (see Bergström et al., 2007). Furthermore, including not-learned items in the follow-up analysis provided a baseline measure for assessing the extent of success at recollection avoidance of learned no-think items because item-specific memory was absent for the not-learned items. Not-learned items were expected to have overall most negative parietal ERPs in the typical parietal EM effect time window, reflecting a lack of recollection of those items, but parietal ERPs for learned no-think items should be reduced to similar levels if recollection avoidance was successful.

ERP Statistical Analysis

The main ERP statistical analysis was conducted using ''nonrotated'' spatio-temporal task partial least squares (PLS), a multivariate statistical technique that allows examination of distributed patterns of spatial and temporal dependencies in the ERP data (Kovacevic & McIntosh, 2007; McIntosh, Chau, & Protzner, 2004; McIntosh & Lobaugh, 2004; Düzel et al., 2003; Lobaugh, West, & McIntosh, 2001; McIntosh, Bookstein, Haxby, & Grady, 1996). PLS computes the ''cross-block'' covariance between a matrix of dependent measures (the spatio-temporal ERP distribution) and a set of exogenous measures, in this case, orthogonal contrast vectors representing the experimental conditions (the number of contrasts equal to the degrees of freedom in the experimental design), thereby constraining the solution to covariance attributable to the experimental manipulation (McIntosh & Lobaugh, 2004). The PLS analysis outputs latent variables (LVs) that contain 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. In nonrotated PLS (Kovacevic & McIntosh, 2007; McIntosh & Lobaugh, 2004), a priori defined contrasts are used as the design saliences of the LVs, and it thus allows a direct assessment of the hypothesized experimental effects. The sums of squares of the cross-block covariance between each contrast matrix and the spatio-temporal data matrix are used as singular values and are tested for significance using permutation test, where each participant's data are randomly reassigned without replacement to different experimental conditions and the sums of squares recomputed. After a large number of such randomizations, the number of times the sums of squares of the permutation exceeded the sums of squares of the observed data 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 electrode saliences are then recalculated for each bootstrap sample. The ratio of the electrode salience to the bootstrap standard error gives a standardized measure of reliability that is approximately equivalent to a z score, whereby values above 1.96 and below −1.96 are reliably different from zero with a 95% confidence interval (CI) if the bootstrap distribution is normal (McIntosh & Lobaugh, 2004).

PLS has some major advantages to traditional univariate analysis of mean amplitudes: PLS requires no initial assumptions regarding temporal or spatial properties of the experimental effects, and thus, minimizes the subjective aspects of choosing which time windows and electrode locations to perform analysis on. Because PLS is a multivariate technique, it is more powerful than univariate techniques when analyzing correlated brain data (see McIntosh et al., 2004). The statistical assessment is applied at the level of the full spatio-temporal pattern so the number of statistical tests is minimized. Bootstrap testing involves *reliability* rather than significance testing so no corrections for multiple comparisons are necessary for the bootstrap stage because no further statistical test is performed. The analysis was conducted using the PLSgui software from the Rotman Research Institute, which runs in Matlab and is available for download at (www.rotman-baycrest.on.ca/pls).

In the current analysis, nonrotated PLS was computed separately for the first and second half of the presentations, using three orthonormal contrasts for each half, which represented the main effect of first half think/no-think instruction, the main effect of second half think/no-think instruction and their interaction term. The PLS was computed for all scalp electrodes across a time window from 0 to 1500 msec. A total of 1000 permutations were used to estimate the significance of each contrast, and the reliability of the electrode saliences was estimated using 200 bootstraps. Significant main effects received no follow-up analysis, and instead, the bootstrap ratios of the electrode saliences of the significant main effect contrasts were used directly to determine which time windows and locations that reliably showed the effect (i.e., values above 1.96 or below −1.96 were considered reliable as they were different from zero with a 95% CI). Significant interactions were followed up by simple comparisons on mean amplitudes at electrodes and within 100 msec time windows that were identified by the bootstrap ratios of the electrode saliences of the PLS contrast as reliably expressing the interaction with a 95% CI. We focused our follow-up analysis on effects expressed during the first 1000 msec of the epoch because this includes the time during which recollection-related effects typically take place.

RESULTS

Behavioral Results

In the initial test of learning (cued recall test) at the end of the study phase, 71% of associate words were recalled on average (range = 45–93%, *SEM* = 3.1%). Correct recall of associate words in response to their respective cue words in the final cued recall test was calculated on an individual-participant basis as a percentage of the number of items recalled in the initial test. Mean accuracy was T–T = 99.1%, *SEM* = 0.6%; T–NT = 98.8%, *SEM* = 0.9%; NT–T = 94.7%, *SEM* = 2.0%; and NT–NT = 95.8, *SEM* = 1.5%. For items recalled in the initial test, there was no significant difference in final recall mean accuracy between the four conditions [there was a nonsignificant trend for final recall to be lower for the two conditions with no-think instruction in the first half compared to the two conditions with a think instruction in the first half: one-way repeated measures ANOVA with the four conditions as levels: $F(2.1, 47.7) = 2.5$, $p = .09$, Greenhouse–Geisser corrected]. Because items were only included in the ERP conditions that were recalled both in the initial test and in the final cued recall test, the absence of a significant difference in final recall accuracy meant that approximately equal numbers of ERP observations were available for the four conditions.

Mean participant ratings of difficulty of and success in avoiding recollection of no-think associates after each block of presentations are presented in Figure 1. Ratings were collected after each behavioral block of four presentations of each cue word [as opposed to the ERP data, which were averaged collapsed across the first two behavioral blocks (i.e., the first half of presentations) and separately averaged across the following two behavioral blocks (i.e., the second half of presentations) to ensure sufficient signal-to-noise ratio in the ERP averages]. As a result, the reversal in think/no-think instructions for half of the items occurred between behavioral Blocks 2 and 3. One-way repeated measures ANOVAs with the four blocks as levels revealed significant omnibus effects of block on both difficulty [$F(2.2, 50.4) = 12.9$, $p < .001$, Greenhouse–Geisser corrected] and success ratings [$F(2.1, 49.3) = 14.3$, $p < .001$, Greenhouse–Geisser corrected]. Paired-sample t tests (against Bonferroni-corrected α of .0125 for four family-wise comparisons) revealed that whereas rated difficulty was significantly higher for Block 1 than for Block 2 [$t(23) = 8.3$, $p < .001$] and significantly higher for Block 3 than for Block 4 [$t(23) = 3.8$, $p < .001$], there were no significant differences in rated difficulty between Block 1 and Block 3 [$t(23) = 1.1$, $p > .3$] or between Block 2 and Block 4 ($t < 1$). Ratings of success at avoiding recollection were significantly lower for Block 1 than for Block 2 [$t(23) = 5.9$, $p < .001$] and significantly lower for Block 3 than for Block 4 [$t(23) = 4.7$, $p < .001$], but again there were no significant differences in rated success between Blocks 1 and 3 [$t(23) = 1.6$, $p > .1$] or Blocks 2 and 4 [$t(23) = 1.9$, $p > .06$]. When ratings were collapsed across Blocks 1 and 2 and across Blocks 3 and 4 to enable a contrast between first half and second half ratings (in order to compare to ERP effects that were also collapsed across first and second halves of the think/no-think phase),

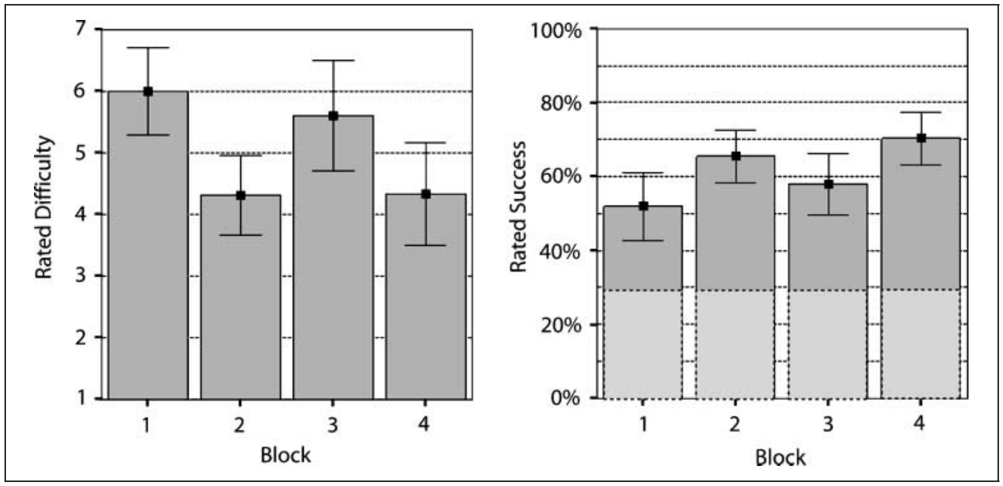

Figure 1. Participants' average self-reported ratings of difficulty and success at avoiding recollection during each block of presentations. Left: Average participant ratings of how difficult it was to avoid recollection of no-think associates in each block, on a scale between 1 (*extremely easy*) to 7 (*extremely difficult*). Right: Average participant estimates of the percentage of trials in each block on which they succeeded to avoid recollection of no-think associates. The lighter shade in the base of the bars represents the mean percentage of items that were not initially learned. Error bars depict the 95% confidence interval for the means.

rated difficulty in avoiding recollection only marginally decreased from the first (M = 5.2, SEM = 0.3) to the second half [M = 5.0, SEM = 0.4; paired $t < 1$; on a scale between 1 (*extremely easy*) to 7 (*extremely difficult*)]. Participants rated that they were successful at avoiding recollection on 5% more of the no-think trials in the second half (M = 64.1%, SEM = 3.5%) than in the first half (M = 58.6%, SEM = 3.8%), a difference that was a nonsignificant trend [paired $t(23) = 2.0$, $p < .07$].

The results of the posttesting questionnaire (courtesy of Benjamin J. Levy and Michael C. Anderson) revealed that there was large individual variability in preferred strategies for avoiding recollection (items are summarized for brevity).[3] The most frequently reported strategies were to "try to make the response leave mind by shifting attention to something else," "first push the memory out of mind, and to make sure it stayed out, shift attention to something else," or to "focus on the individual letters of the word, or the word's overall visual appearance, in order to prevent the response from coming to mind." Correlations between the behavioral data and the ERP effects are presented in a later section.

ERP Results

ERPs reported here were recorded during the think/no-think phase intervening between the study phase and the final cued recall test.

First Half

Figure 2 shows, for the four ERP conditions in the first half of the think/no-think phase, the grand-average waveforms recorded from electrodes at left and right fronto-polar sites; left, midline, and right frontal sites; the midline centro-parietal site; and left, midline, and right parietal sites.

The nonrotated PLS revealed that the only contrast that was significantly expressed in the spatio-temporal data during the first half was a main effect of first half think versus no-think instructions ($p < .01$). Neither the main effect of second half instruction nor the interaction between first and second half instructions neared significance (both ps $> .4$). The contrast between first half think and no-think instructions accounted for 49.88% of the cross-block covariance. The bootstrap test of the electrode saliences of this contrast indicated that first half think conditions had reliably more positive amplitudes than first half no-think conditions across right central electrodes between around 350 and 450 msec poststimulus, and across left temporo-parietal regions between around 450 and 800 msec poststimulus, with a simultaneous polarity reversal so that first half think conditions had reliably more negative amplitudes than first half no-think conditions across right frontal sites. This contrast and the bootstrap ratios of its electrode saliences to their standard errors are presented in Figure 3.

In summary, in the first half of the think/no-think phase, ERPs showed only modulations caused by the first half think versus no-think instructions. The most reliable and temporally extended modulation replicates the findings of Bergström et al. (2007) of a larger late left parietal positivity for think compared to no-think trials, but there was also a weaker earlier right central positivity for think compared to no-think trials.

Second Half

Figure 4 shows, for the four ERP conditions in the second half of the think/no-think phase, the grand-average waveforms recorded from electrodes at left and right fronto-polar sites; left, midline, and right frontal sites; the midline centro-parietal site; and left, midline, and right parietal sites.

The nonrotated PLS on the second half spatio-temporal data revealed that the main effect of first half think versus no-think instructions was no longer significant (p = .07) and accounted for only 28.28% of the cross-block covariance.[4] Instead, there was now a significant main effect of second half think versus no-think instructions ($p <$ .01, accounting for 36.11% of cross-block covariance) and the bootstrap ratio of the electrode saliences indicated that the second half think conditions had reliably more positive amplitudes than second half no-think conditions across central and left parietal regions between around 450 and 650 msec poststimulus. This effect became more left-lateralized across left temporo-parietal regions during 650 to 800 msec poststimulus. Similar to the think/no-think effect in the first half, there was a polarity reversal so that second half think conditions had reliably more negative amplitudes than second half no-think conditions across right frontal sites, although this time emerging later than the parietal effect from around 600 to 800 msec poststimulus. This contrast and the bootstrap ratios of its electrode saliences to their standard errors are presented in Figure 5A and 5B. The magnitudes of the bootstrap ratios indicated that the main effect of second half think/no-think instructions during the second half of the presentations was more reliable across left parietal sites than the main effect of first half think/no-think instructions had been during the first half of the presentations (see Figure 5B vs. Figure 3B).

In addition, the PLS contrast representing the interaction between first and second half think/no-think instructions was also significant in the second half ($p <$ .01, accounting for 35.71% of cross-block covariance).

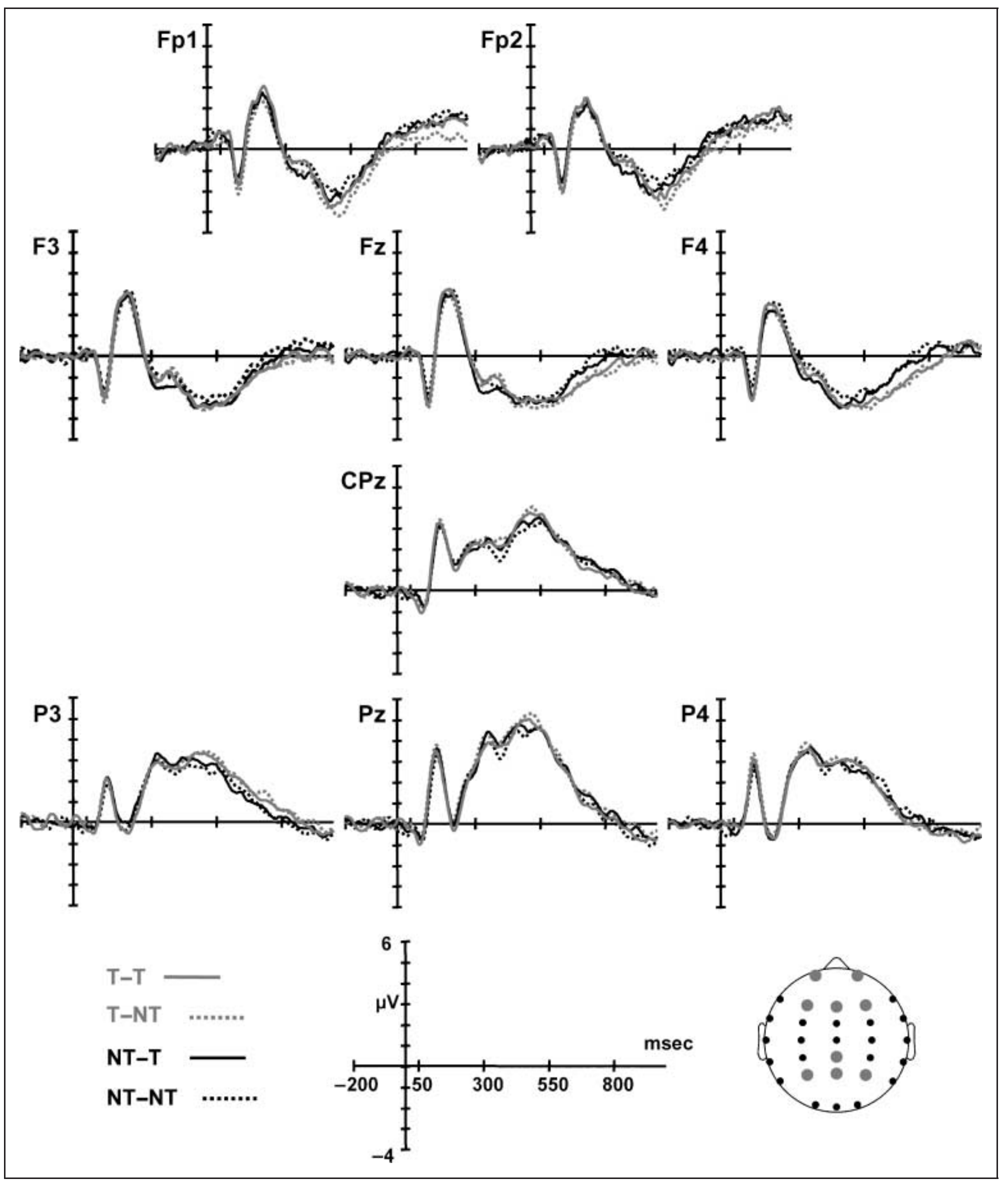

Figure 2. Grand-average ERPs for the four experimental conditions during the first half of presentations at left (Fp1) and right (Fp2) fronto-polar sites; left (F3), midline (Fz), and right (F4) frontal sites; the midline centro-parietal site (CPz); and left (P3), midline (Pz), and right (P4) parietal sites. The head-plot in the right bottom corner depicts the electrode locations (the coordinates of the electrode sites have been shifted toward the vertex in order to fit within the head radius).

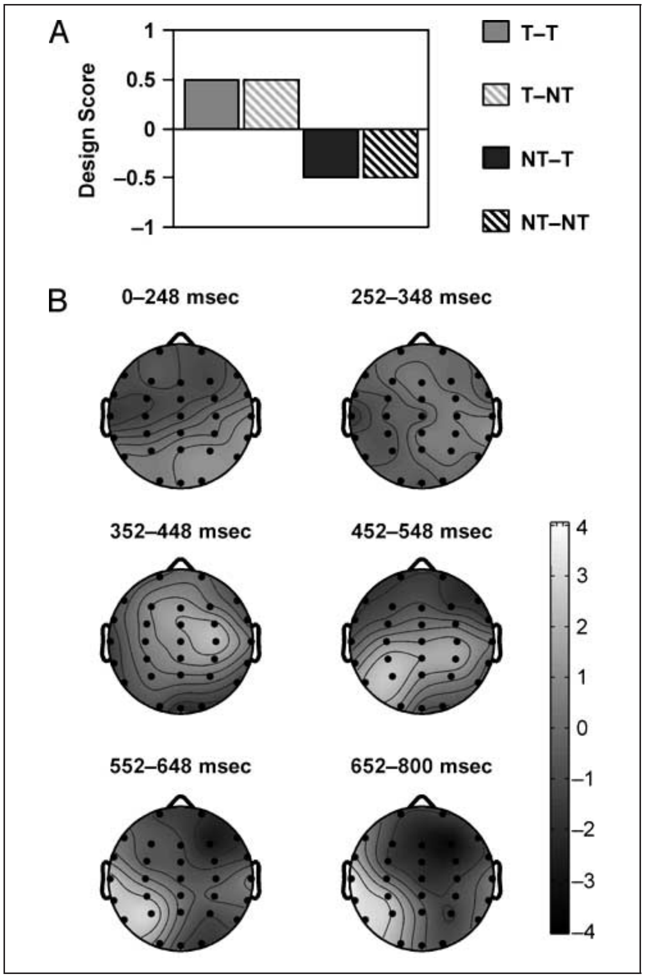

Figure 3. The significant latent variable (LV) in the nonrotated task-PLS analysis of ERPs during the first half of think/no-think presentations. This LV expresses a main effect of first half think versus no-think instructions (cross-block covariance accounted for by this LV = 49.88%, $p < .01$). (A) The design contrast of the LV. (B) 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 reliable with a 95% CI. 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.

The bootstrap test of the electrode saliences indicated that this interaction effect was reliable across centro-parietal sites as early as from approx. 250 to 550 msec poststimulus, with a later emerging interaction in the reverse direction across bilateral frontal sites, maximal between around 450 and 650 msec poststimulus. This contrast and the bootstrap ratios of its electrode saliences to their standard errors are presented in Figure 5C and D.

To clarify the nature of the interaction effect, simple comparison paired *t* tests were performed at two sites that maximally showed the interaction as identified by the PLS, the right fronto-polar site (Fp2), and the midline centro-parietal site (CPz), in four time windows that best captured the effect, 252 to 348 msec, and 352 to 448 msec, 452 to 548 msec and 552 to 648 msec, as presented in Table 1. Across centro-parietal regions, the ERPs for items which had changed to having a no-think instruction from having a think instruction (i.e., the T–NT condition) had more negative amplitudes from 252 to 648 msec compared to the items that continued to be presented with a think instruction (i.e., the T–T condition), and also had more negative amplitudes than the items which had been presented with no-think instructions in both halves (i.e., the NT–NT condition) between 252 and 548 msec. In the earlier two time windows (252 to 348 msec and 352 to 448 msec), the other conditions were not significantly different from each other, all having more positive amplitudes than the T–NT condition.

In the later time windows (452 to 548 msec and 552 to 648 msec) at the centro-parietal site, however, the items that had changed to a think instruction from a no-think instruction (i.e., the NT–T condition) had more positive amplitudes than the items that continued to be presented with a no-think instruction (i.e., the NT–NT condition), consistent with the PLS results of a significant main effect of second half instruction across parietal sites in these later time windows.

At the right fronto-polar site, the pattern of effects was rather different. In the earliest time window (252 to 348 msec), the only significant difference was a more negative ERP for the items that had been presented with think instructions in both halves (the T–T condition) compared to items that had changed to a think from a no-think instruction (the NT–T condition). In the 352 to 448 msec time window, items that had been presented with think instructions in both halves still had the most negative-going ERPs, but now only significantly more negative than ERPs for items that had changed to a no-think from a think instruction (the T–NT condition), and this effect remained significant also in the 452 to 548 msec and 552 to 648 msec time windows. In addition, in the 452 to 548 msec window, the T–T condition again had significantly more negative amplitudes than the NT–T condition, and now the items that had been presented with no-think instructions in both halves (the NT–NT condition) had more negative amplitudes than items that had changed to no-think from think instructions (the NT–T condition).

The early negativity seen specifically for T–NT items across centro-parietal sites carried over into the later 452–548 time window, causing these items to have particularly negative ERPs also in this time window. Because we were particularly interested in whether the ERP correlate of recollection—which typically emerges around 400–500 msec poststimulus—could be voluntarily reduced for items that swapped from a think to no-think instruction, we were concerned that the early negativity might be masking a later recollection-related increase in positivity for T–NT items. To disentangle this early negativity from the later think/no-think main effect, we calculated a measure of parietal positivity increase from the average of the earlier (252–448 msec) time windows to the 452–548 msec time window, in order to compensate for potential carryover of the earlier increased negativity. This measure was computed for each condition at left (CP3), midline (CPz), and right (CP4) centro-parietal sites, and left (P3), midline (Pz), and right (P4) parietal separately, and these difference scores were tested for significant differences between conditions. Two-way repeated measures ANOVAs with the factors First half think/no-think instruction × Second half think/no-think instruction revealed only significant main effects of second half instructions at all sites [CP3: $F = 5.6$, $p < .05$; CPz: $F = 7.8$, $p < .05$; CP4: $F = 9.9$, $p < .01$; P3: $F = 8.1$, $p < .01$; Pz: $F = 7.3$, $p < .05$; P4: $F = 5.6$, $p < .05$; all *df*s(1, 23)], but no significant main effects of first half instruction and no significant interactions between first and second half instructions (all *p*s > .17). The significant main effects of second half instruction were, in all cases, caused by significantly larger positivity increases from the earlier to the late time window for the two conditions with second half think instructions than the corresponding increase for the conditions with second half no-think instructions. Thus, the two no-think conditions did not significantly differ from each other in the amount of recollection-related positivity increase across parietal and centro-parietal sites from the average of 252–448 msec to the 452–548 msec time window, but their positivity increase was significantly smaller than the corresponding increase for the two think conditions, which did not differ from each other.

In sum, in the earlier part of the epoch from around 250 msec onward, there was a reduction in centro-parietal positivity for the items that had changed from think to no-think instructions, compared to the other

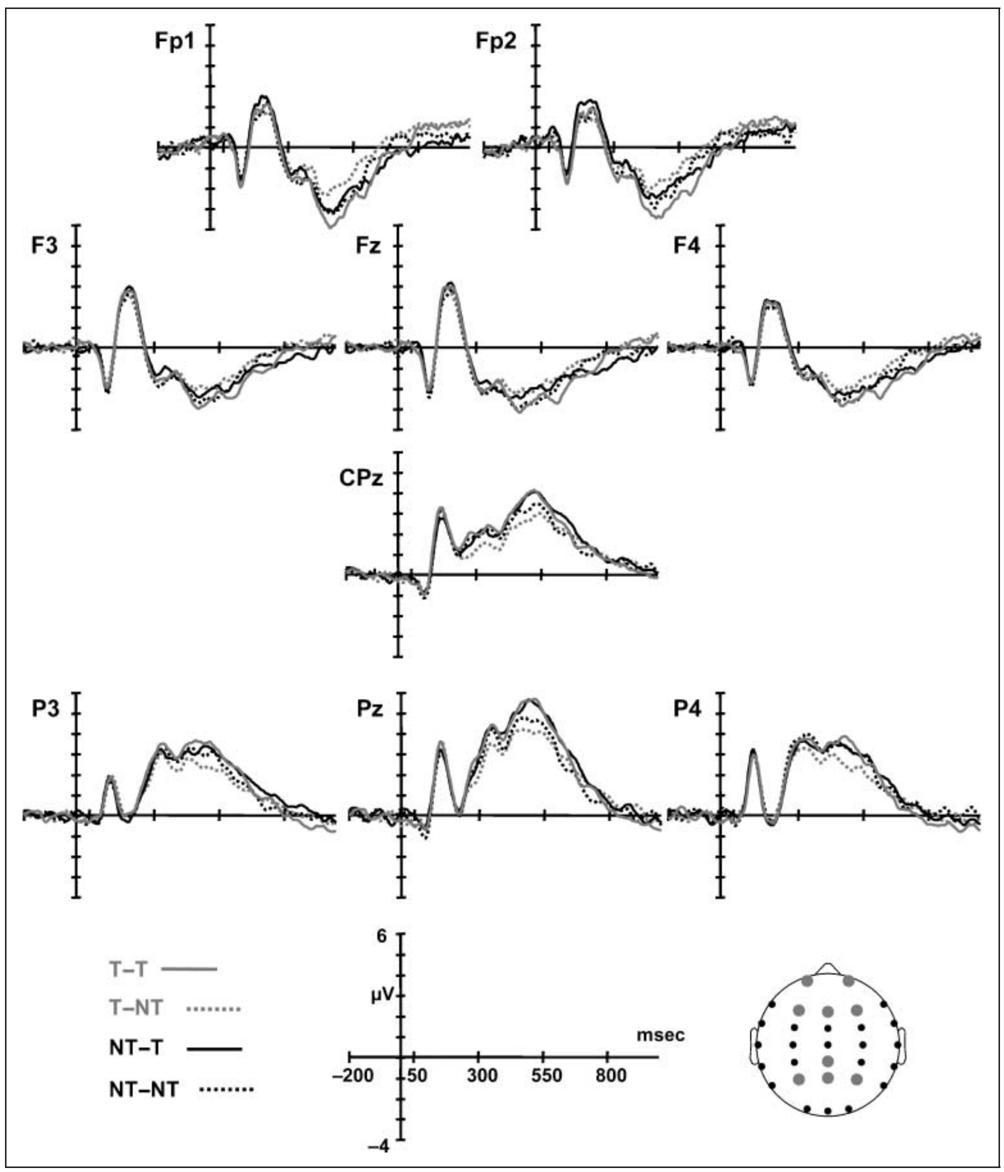

Figure 4. Grand-average ERPs for the four experimental conditions during the second half of presentations at left (Fp1) and right (Fp2) fronto-polar sites; left (F3), midline (Fz), and right (F4) frontal sites; the midline centro-parietal site (CPz); and left (P3), midline (Pz), and right (P4) parietal sites. The head-plot in the right bottom corner depicts the electrode locations (the coordinates of the electrode sites have been shifted toward the vertex in order to fit within the head radius).

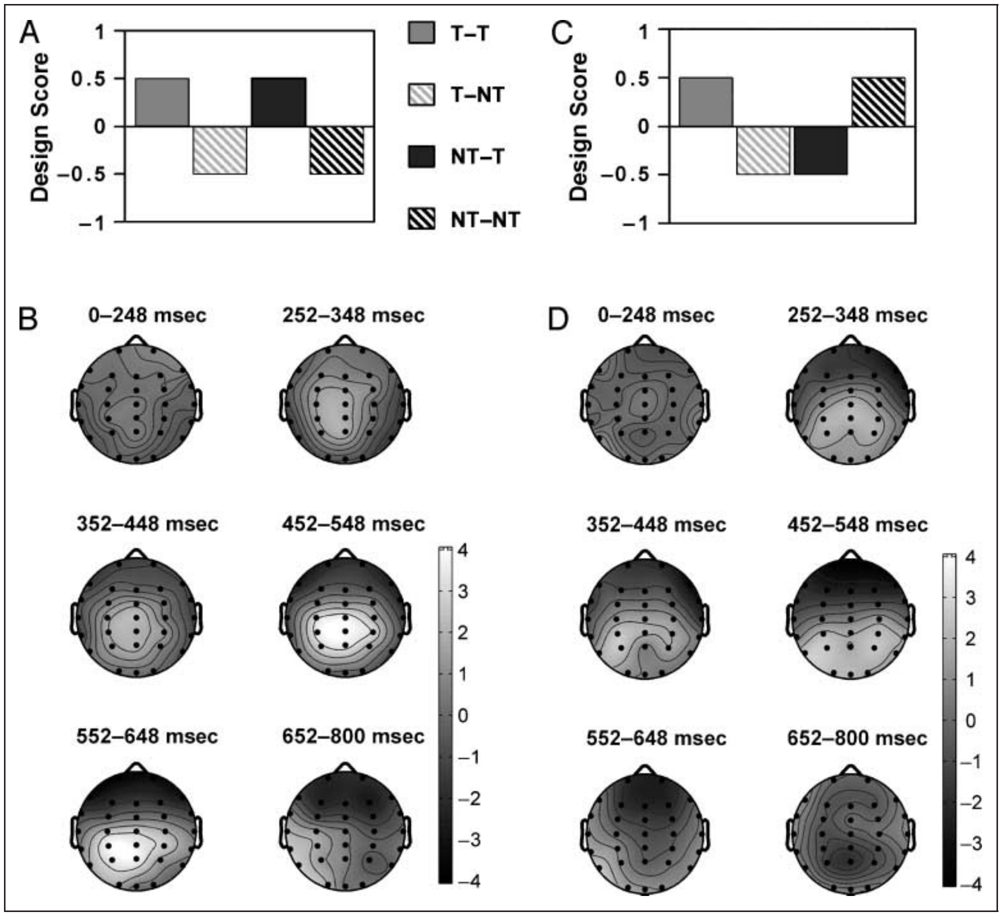

Figure 5. The significant latent variables (LV) in the nonrotated task-PLS analysis of ERPs during the second half of think/no-think presentations. The first LV (A and B) expresses a main effect of second half think versus no-think instructions (cross-block covariance accounted for by this LV = 36.11%, $p < .01$). (A) The design contrast of the LV. (B) 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 reliable with a 95% CI. 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. The second LV (C and D) expresses an interaction between first half and second half think versus no-think instructions (cross-block covariance accounted for by this LV = 35.71%, $p < .01$). (C) The design contrast of the LV. (D) Topographic maps of the bootstrap ratio of the electrode saliences of the LV to their standard error.

Table 1. Paired t Tests of ERP Mean Amplitudes at the Midline Centro-parietal Site (CPz) and the Right Fronto-polar Site (Fp2) during the Second Half of Presentations in Four Time Windows that Best Captured the Interaction Effect between First and Second Half Think/No-Think Instructions

			252–348 msec		*352–448 msec*		*452–548 msec*		*542–648 msec*	
Location	*Pair*	*df*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
Centro-parietal midline (CPz)	T–T vs. T–NT	23	3.3	.01	2.6	.01	4.6	.001	2.6	.02
	T–T vs. NT–T	23	–	–	–	–	–	–	–	–
	NT–NT vs. NT–T	23	–	–	–	–	2.1	.05	2.8	.01
	NT–NT vs. T–NT	23	3.2	.01	2.3	.03	3.0	.01	–	–
Right fronto-polar (Fp2)	T–T vs. T–NT	23	–	–	2.6	.02	4.8	.001	5.5	.001
	T–T vs. NT–T	23	2.6	.02	–	–	3.6	.001	–	–
	NT–NT vs. NT–T	23	–	–	–	–	–	–	–	–
	NT–NT vs. T–NT	23	–	–	–	–	2.4	.03	–	–

Conditions are items that had a think instruction during the first half and second half of presentations (T–T), items that had a think instruction during the first half of presentations but changed to a no-think instruction during the second half (T–NT), items that had a no-think instruction during the first half and second half of presentations (NT–NT), and items that had a no-think instruction during the first half of presentations but changed to a think instruction during the second half (NT–T).

three conditions. Although this interaction carried over into the 452–548 msec time window, it was separable from a main effect of second half think/no-think instruction, which was manifest as a centro-parietal positivity increase for the two think conditions compared to the two no-think conditions between 452 and 648 msec. In the earlier time window, the strongest effect across frontal sites, however, appeared to be more negative amplitudes for items that had been presented with think instructions in both halves compared to the other conditions, in particular, compared to the items that had changed from a think instruction in the first half to a no-think instruction in the second half, which had the most positive amplitudes.

The results show that reversing think/no-think instructions for some items between the first and second half of presentations resulted in a reversal of the amplitude of parietal positivity maximal between 450 and 650 msec, whereas items that were presented with the same think/no-think instructions in the first and second half did not show a reversal of the amplitude of parietal positivity. This is clearly illustrated in Figure 6, which displays the grand-average waveforms for all ERP conditions (A and C) in the first and second half of the think/no-think phase at the midline parietal site (where the reversal was most visible), and topographic maps of the difference in mean amplitudes between 452 and 548 msec between the two conditions that reversed instructions (B) and the two conditions that did not reverse instructions (D).

The Memory-specific Nature of the Parietal EM Effect Modulation

The follow-up analysis included ERPs from a subset of 10 participants, and compared their ERPs for the demonstrably learned conditions from the main analysis against their ERPs for not-learned items (see section on EEG Recording and Data Processing for method and rationale). First and second half ERPs for these learned and not-learned conditions at the left parietal site P3 (the location typically used for testing recollection-related ERP effects), and mean amplitudes between 452 and 548 msec at the same site (the time window when the parietal EM effect was most reliable), are presented in Figure 7. As can be seen in this figure, the subset of 10 participants showed the same pattern of parietal ERP results for learned items in both the first and second halves as the full sample did in the main analysis, but there were very little effects of think/no-think instructions on parietal ERP amplitudes for not-learned items.

During the first half, learned items with a think instruction showed particularly enhanced left parietal positivities compared to learned no-think and both not-learned conditions. Although there was a slightly enhanced positivity also for not-learned think compared to not-learned no-think items, this effect was smaller than

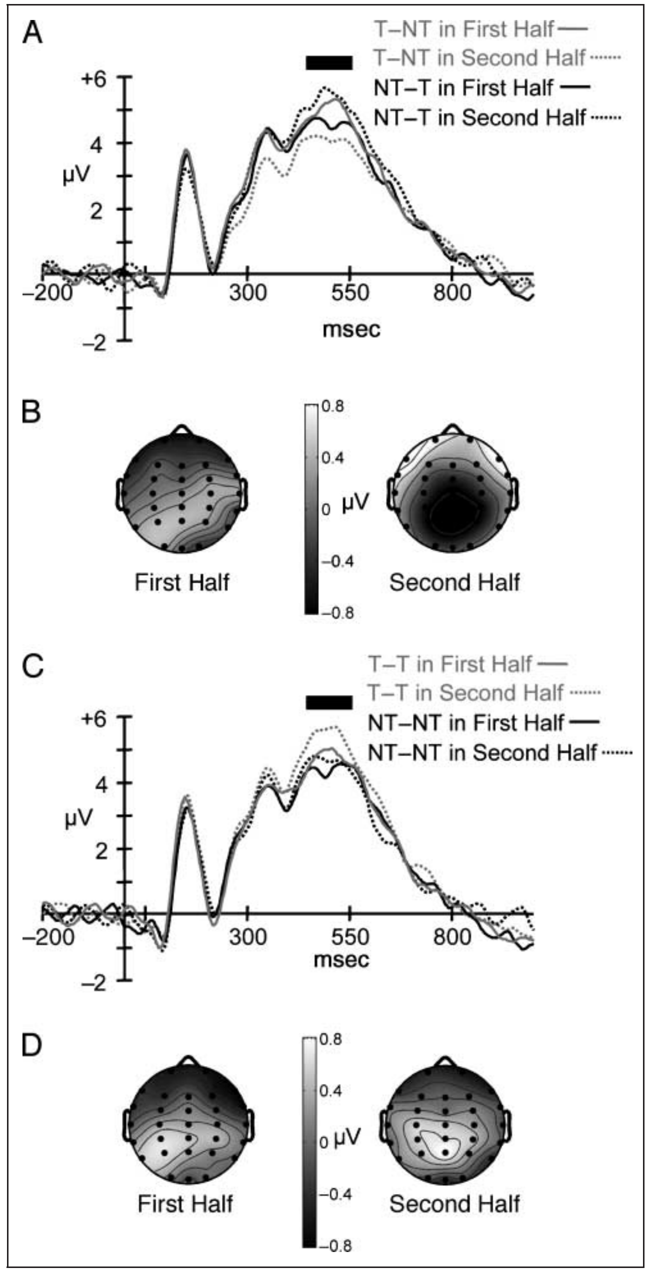

Figure 6. Grand-average ERPs and topographic maps comparing the two conditions that reversed instructions (A and B) and the two conditions that did not reverse instructions (C and D) during the first and second half of presentations at the midline parietal site (Pz). (A) First and second half grand-average ERPs for the conditions that reversed instructions (T–NT and NT–T). The black line above the ERP graph indicates the time window displayed in the topographic maps below (B). (B) Topographic maps of the average amplitude difference between the T–NT and NT–T conditions (NT–T subtracted from T–NT) between 452 and 548 msec (map scale 0.8 to −0.8 μV). (C) First and second half grand-average ERPs for the two conditions that did not reverse instructions (T–T and NT–NT). The black line above the ERP graph indicates the time window displayed in the topographic maps below (D). (D) Topographic maps of the average amplitude difference between the T–T and NT–NT conditions (NT–NT subtracted from T–T) between 452 and 548 msec (map scale 0.8 to −0.8 μV). Whereas the amplitude difference between T–NT and NT–T clearly reverses polarity between the first and second half (A and B), there is no corresponding reversal in amplitudes between T–T and NT–NT (C and D).

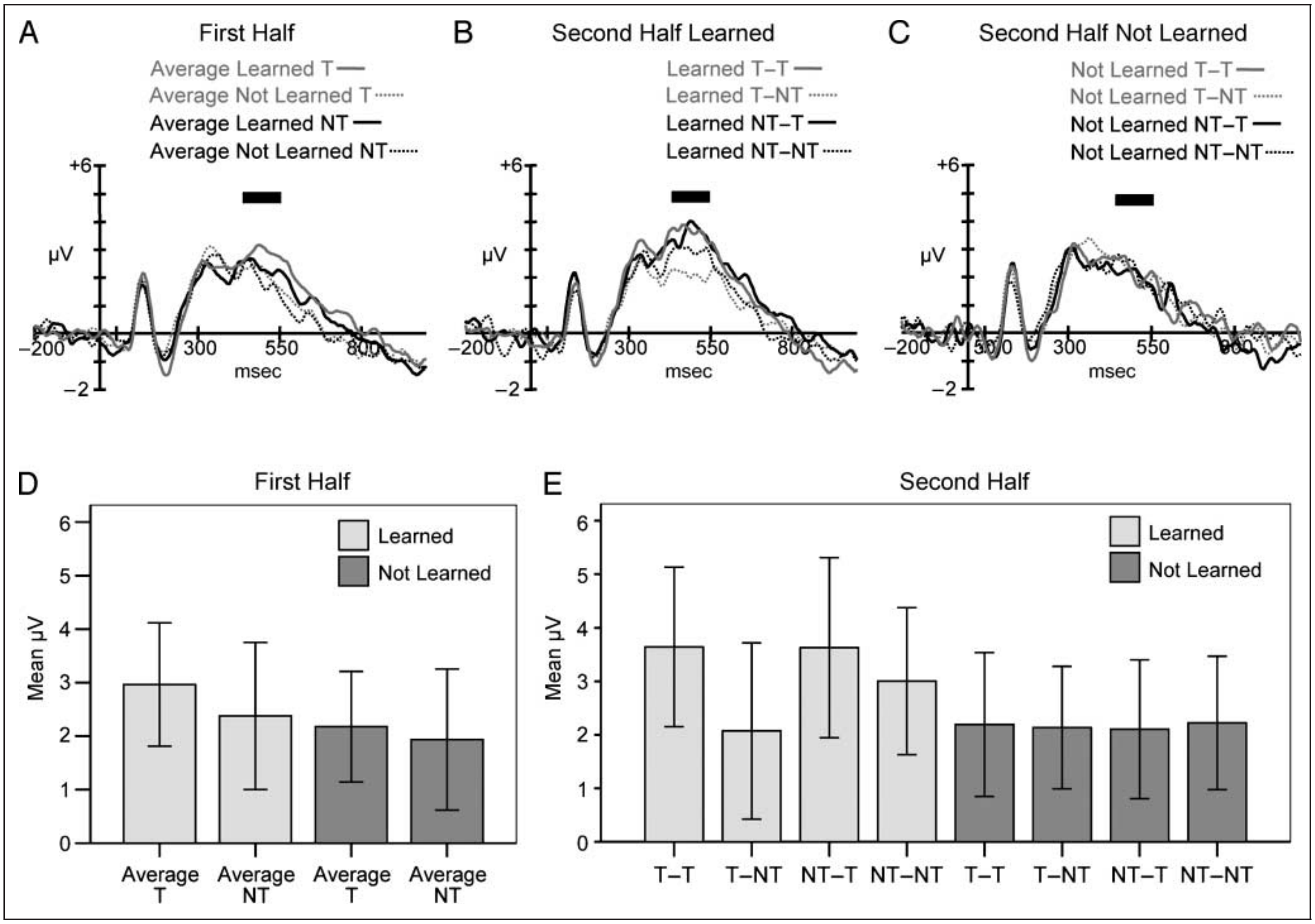

Figure 7. Grand-average ERPs and mean amplitudes at the left parietal site (P3) from the follow-up learning analysis. (A) Grand-average ERPs for the average learned and not learned first half think and no-think conditions (collapsed across second half think/no-think condition) during the first half of the think/no-think phase. The black line above the ERP graph indicates the time window of the mean amplitudes displayed in the bar chart below (D). (B and C) Grand-average ERPs during the second half of the think/no-think phase for: (B) the four learned ERP conditions; and (C) the four not-learned ERP conditions, separated dependent on first half and second half think/no-think condition. The black lines above the ERP graphs indicate the time window of the mean amplitudes displayed in the bar chart below (E). (D and E) Mean amplitudes between 452 and 548 msec for: (D) the average learned and not learned first half think and no-think conditions during the first half of the think/no-think phase; and (E) the learned and not learned T–T, T–NT, NT–T, and NT–NT conditions during the second half of the think/no-think phase. Error bars depict the 95% confidence interval for the means.

the corresponding effect for learned items (highly similar to Bergström et al.'s [2007] results). This pattern was confirmed by a two-way repeated measures ANOVA with the factors Think/No-Think instruction × Learning on the first half mean amplitude data (as above), which in addition to a significant main effect of learning [$F(1, 9) = 6.2$, $p < .05$] and a trend-level main effect of think/no-think instruction [$F(1, 9) = 3.9$, $p < .09$], also revealed a significant interaction between learning and think/no-think instruction [$F(1, 9) = 7.2$, $p < .05$]. Paired t tests confirmed that the learned think condition was more positive than the not learned think [$t(9) = 3.6$, $p < .01$] and the learned no-think conditions [$t(9) = 2.8$, $p < .05$], but there were no significant differences between the learned no-think condition and the not-learned no-think condition [$t(9) = 1.5$, $p > .15$] or between the two not-learned conditions [$t(9) = 1.1$, $p > .3$].

During the second half, the two learned conditions with second half think instructions had particularly positive parietal ERPs, whereas the two learned conditions with second half no-think instructions had less positive ERPs, and in particular, items that had swapped from a prior think to a no-think instruction—mirroring the pattern found in the main analysis. Not-learned items had overall most negative ERPs (although approximately equivalent to the learned T–NT items), and there were virtually no differences between not-learned items in mean parietal amplitudes in this time window. This pattern was confirmed by a three-way repeated measures ANOVA with the factors First half think/no-think instruction × Second half think/no-think instruction × Learning on the second half mean amplitude data[5], which confirmed that, in addition to significant main effects of learning [$F(1, 9) = 16.1$, $p < .01$] and second half think/no-think instruction [$F(1, 9) = 2.5$, $p < .05$], the interaction between learning and second half think/no-think instruction was highly significant [$F(1, 9) = 14.6$, $p < .01$]. There was also a trend-level interaction between first and second half think/no-think instructions [$F(1, 9) = 4.0$, $p < .08$], but no other significant effects. Testing the effect of second half think/no-think instruction (collapsed across the levels of first half think/no-think instruction) separately for learned and not-learned items confirmed that the items with a second half think instruction had significantly more positive parietal ERPs than items with a second half no-think instruction only when they were successfully learned [$t(9) = 3.5$, $p < .01$], but not when they were not learned ($t < 1$). Testing the effect of learning separately for items with a second half think instruction and items with a second half no-think instruction (again collapsed across first half think/no-think instruction) confirmed that the learned items had significantly more positive parietal ERPs than not-learned items only when presented with a second half think instruction [$t(9) = 5.3$, $p < .001$], but not when presented with a second half no-think instruction [$t(9) = 1.3$, $p > .2$].

In sum, the results of the follow-up analysis that compared the ERPs for think and no-think items that were either successfully learned or not successfully learned confirm that the parietal ERP modulations between 452 and 548 msec were dependent on item-specific memory, and that the parietal ERPs for learned no-think items in this time window were similar to the ERPs for not-learned items. The fact that a subset of only 10 participants showed the same pattern of ERP effects for learned items as that found in the main analysis illustrates the high reliability of these parietal EM effect modulations.

Correlations between Behavioral Data and the ERP Effects

To correlate the behavioral data and the parietal EM effect, first, an overall think/no-think left parietal effect on site P3 was computed by averaging together mean amplitudes between 452 and 548 msec for ERP conditions with a think instruction in the first half and ERP conditions with a think instruction in the second half, and subtracting the average of ERP conditions with a no-think instruction in the first and second half. This effect was correlated with participants' overall self-reported difficulty in avoiding recollection (averaged across all blocks), overall self reported success at avoiding recollection (averaged across all blocks) and the questionnaire data (number of items = 23). The ERP effect did not correlate with either self-reported difficulty or success (both *p*s > .5), and only correlated significantly with one questionnaire item: "I didn't actively try to make the response leave my mind. However, I did actively resist acknowledging or attending to the memory while it was in my mind. So, I didn't push it out or even try to divert my thoughts at all, but I did actively disregard the response's presence" (nonparametric $r_s = .6$, significant against Bonferroni-corrected $\alpha = .002$ for 25 pairwise correlations).

To establish whether the early negativity seen for T–NT items across centro-parietal sites during the second half was related to the self-report data, we also computed difference scores for T–NT subtracted from the average of the other three conditions (because these showed no early differences across centro-parietal sites) at midline centro-parietal (CPz) and parietal (Pz) sites (where the effect was maximal) during the two early time windows (252–348 msec and 352–448 msec), and correlated these scores with overall self-reported difficulty and success at avoiding recollection and the questionnaire data (same as above). There were no significant correlations between these difference scores and the behavioral data at the corrected α-level.

DISCUSSION

The current experiment investigated whether automatic recollection can be voluntarily avoided, as indexed by the ERP correlate of conscious recollection—the parietal EM effect (e.g., Rugg & Curran, 2007; Friedman & Johnson, 2000; Rugg et al., 1996; Smith, 1993; Paller & Kutas, 1992). We found significant modulations of the parietal EM effect as a function of whether participants were asked to recollect or to avoid recollecting the memory, indicating that participants could successfully control recollection. Importantly, switching instructions for some items so that participants had to avoid recall of words they had previously repeatedly recalled, and vice versa, reversed the parietal EM effect for those items, suggesting that avoiding recollection is possible even when recall is highly overpracticed. The follow-up analysis confirmed that these parietal modulations were, in line with prior results (Bergström et al., 2007), specifically dependent on whether participant had successfully learned the associated response, thereby strongly supporting the view that the effects reflected recollection or recollection avoidance of specific items, rather than memory-unspecific, task-related processes. Furthermore, avoiding recollection of learned items reduced the parietal EM effect to similar levels as parietal ERPs for items that had not been successfully learned in the first place. This latter result suggests that attempts at avoiding recollection of learned items were overall highly successful, as little recollection would be expected to take place for not-learned items (Bergström et al., 2007; Rugg et al., 1996). The results thus support the notion that voluntary control processes can successfully override automatic recollection (Anderson et al., 2004; Levy & Anderson, 2002; Anderson & Green, 2001).

Self-reports

Participants' self-reports indicated that they found avoiding recollection difficult throughout the experiment, particularly in the beginning of the think/no-think phase, and also after some items had swapped from a think to a no-think instruction. They reported succeeding in avoiding recollection, on average, around 50% of the trials in the beginning of the think/no-think phase, a figure that increased with practice but decreased when some items swapped from a think to a no-think instruction. Average self-reported success in avoiding recollection was at the highest (at the end of the think/no-think phase) at around 70% of the trials so that despite practice, participants estimated that the unwanted memory still came to mind on around 30% of the trials. The self-reported ratings thus indicate that recollection was the prepotent, automatic response to the retrieval cues throughout the think/no-think phase in the current experiment, as participants found it both highly difficult and reported limited success in avoiding recollection. Such a pattern would not be expected if recollection was not the automatic response that had to be actively and effortfully overridden. Having some items swap from a think to no-think instruction appeared to increase the automaticity of recollection for those items because it made recollection avoidance more difficult and avoidance success lower, but recollection seemed to have been the prepotent response also before the swap, as has been previously suggested in the think/no-think task (Anderson et al., 2004; Levy & Anderson, 2002; Anderson & Green, 2001).

First Half ERPs

In the first half of the think/no-think phase, we found the predicted reduction in positivity of the parietal EM effect for items with a first half no-think instruction, replicating Bergström et al. (2007) and suggesting that participants were able to limit recollection of no-think associates during the first half of the phase. This predicted parietal modulation was preceded by a similar increased positivity for think compared to no-think conditions between around 350 and 450 msec poststimulus, but with a scalp distribution maximal across right central electrodes. However, because the first half analysis involved a simple contrast between think and no-think instructions, the functional significance of this unexpected earlier effect is rather unclear. A number of processes are likely to be differentially engaged between the think and no-think conditions, and an increase in positivity across central electrodes around this time window could reflect many of these processes. For example, the effect could reflect some generic task process related to the P300, such as target categorization or increased attentional orienting to think cues (see Polich, 2007 for a recent P300 review). Alternatively, the ERP difference could reflect a strategic, retrieval-related process such as a retrieval attempt elicited by think cues, or a retrieval override attempt elicited by no-think cues. These explanations are not possible to distinguish on the basis on the current data, hence, we instead focus our discussion on the predicted parietal modulation, and most importantly: what happened to the parietal EM effect in the second half of the think/no-think phase when the instructions for some items reversed?

Second Half ERPs

In the second half, the effect of the think/no-think instruction that items had been presented with in the first half was no longer significant. Instead, there was a significant effect of the current, second half think/no-think instruction, with a significantly reduced positivity of the parietal EM effect for items with a second half no-think instruction compared to items with a second half think instruction maximal between 450 and 650 msec, indicating that participants were able to successfully switch recollection or recollection avoidance strategy for items that swapped between the think and no-think conditions, while continuing with an unchanged strategy for items that remained in the same think/no-think condition as in the first half of presentations. The effect of second half think/no-think instructions during the second half of presentations was larger and more reliable than the effect of first half think/no-think instructions during the first half, indicating that—consistent with the self-reports—participants were more successful at performing the task during the second half of presentations, despite the fact that some items had reversed instructions. This finding suggests that *practice* at avoiding recollection was more crucial to the ability to successfully control retrieval of recollectable material than the number of times a particular item had been recollected or avoided.

Furthermore, in the second half of presentations, there was also a significant interaction between first and second half instruction variables, so that the ERPs differed depending on whether items had swapped instructions or not. This effect emerged earlier than typical recollection-related effects, which typically onset at 400–500 msec poststimulus (Rugg & Curran, 2007). In contrast, the interaction effect in the current study was manifest across centro-parietal regions as early as from around 250 msec poststimulus, and consisted of a reduced ERP positivity specifically for items that had swapped from a think to a no-think instruction compared to the other three conditions. Using the amount of positivity increase from the early to later time window as a conservative measure of recollection in the second half, the two conditions with second half think instructions appeared to be associated with approximately equal amounts of recollection, which was significantly more than in the two conditions with second half no-think instructions. Importantly, there was no difference between the two second half no-think conditions in their amount of parietal positivity increase, which suggests that participants were approximately equally successful in avoiding recollection irrespectively of whether the items had swapped from a think to no-think instruction or had been presented with no-think instructions in both halves. Hence, there was no evidence that the early negativity for items that swapped from think to no-think instructions was simply masking a later recollection-related increase in positivity for those items. Because the early ERP negativity and the later parietal modulation were dissociable both on a functional and temporal basis, they are likely to reflect separable cognitive processes.

The early ERP negativity appears to index a process that is specifically involved when people attempt to avoid recollection of particularly prepotent memories. One possibility is that the effect reflects a voluntarily initiated control process, which occurred at an earlier stage than recollection, such as an executive control process that enabled the override of particularly prepotent recollection. Previous fMRI studies have identified a frontal network that show increased activation during no-think trials, which is thought to reflect voluntary control processes aimed at stopping recollection (Depue et al., 2007; Anderson et al., 2004; Anderson & Green, 2001). The early negativity found during particularly prepotent recollection avoidance may reflect some aspect of this executive control network. Admittedly, this hypothesis is rather speculative and would require further research for validation.

Alternatively, the early negativity may not index a voluntary control process, but may instead be a relatively automatic response to the increased interference or conflict associated with items that swapped from over-rehearsed, prepotent recollection to requiring voluntary avoidance of recollection.[6] Interference/conflict-related ERP effects are often manifested as increased negativity, both in long-term memory tasks (proactive interference; Rössner, Rockstroh, Cohen, Wagner, & Elbert, 2000) and in other interference tasks such as the Stroop task (e.g., West, 2003). It has been suggested that some of these Stroop ERP negativities (that are typically found around 350–500 msec poststimulus) reflect conflict detection, and are generated by a source in the ACC (Hanslmayr et al., 2008; West, 2003). Applying the interference framework to our current findings, the early increased negativity for cues that swapped from a think to no-think instruction may reflect a relatively automatic conflict detection/interference process.

In sum, during the second half of presentations, there were two separable ERP effects across central and parietal sites. First, there was an early ERP negativity specifically for items that swapped from requiring repeated recollection to requiring voluntary avoidance of recollection that therefore appeared to reflect a process that is engaged when particularly prepotent retrieval has to be overridden. Second, there was a later emerging (from 450 msec onwards) difference in parietal positivity that varied with second half think/no-think instructions, which was highly similar to the ERP effect that varied with first half think/no-think instructions during the first half of presentations. There are strong reasons to assume that this latter effect reflects voluntary control of recollection, and in the case of items that swapped from a think to a no-think instruction in the second half, voluntary avoidance of prepotent recollection.

Possible Caveats, Future Research, and Implications

The conclusions from the current research are crucially dependent on one assumption: that the parietal ERP modulations found around 450–650 msec reflect differences in the ERP correlate of conscious recollection. This assumption has high face validity because the parietal amplitude reduction occurred specifically when participants were asked to prevent recollection, and the amplitude change had precisely the polarity, timing, and topography that would be expected on the basis of previous research. A very large body of converging literature suggests that a parietal ERP positivity in this time window in memory retrieval tasks reflects conscious reinstatement of episodic information (see e.g., Rugg & Curran, 2007; Friedman & Johnson, 2000; Rugg, 1995). The current results converge with findings from the target/nontarget exclusion task, which suggest that a reduction of parietal ERP positivity during recognition reflects the strategic absence of recollection (e.g., Fraser et al., 2007; Dzulkifli et al., 2006; Dzulkifli & Wilding, 2005; Herron & Wilding, 2005; Wilding et al., 2005; Herron & Rugg, 2003a, 2003b). The results are also consistent with fMRI evidence from two studies that showed reduced recollection-related brain activity during no-think trials (Depue et al., 2007; Anderson et al., 2004). Finally, the conclusion that the parietal EM effect was voluntarily modulated is consistent with participant self-reports that they were indeed attempting to avoid recollection of no-think items, and that they were successful at doing so on a large proportion of trials.[7]

However, the findings from the interference tasks described above (e.g., West, 2003) raise the question of whether some of the ERP effects that are here interpreted as voluntary modulations of the parietal EM effect can be explained by interference/conflict negativities for items with a no-think instruction, as these items are associated with a conflict between the prepotent response (recollection) and the task-appropriate response (avoid recollection). Although it is difficult to conclusively reject this hypothesis, we think it is highly unlikely for several reasons. First and most importantly; the follow-up analysis confirmed that the ERP modulations with the typical timing and location of the parietal EM effect were *memory-specific* (converging with previous findings; Bergström et al., 2007). Think/no-think instructions interacted with the learning status of the associated memory in affecting parietal positivity in a pattern that was highly consistent with the effect indexing the amount of conscious recollection. Parietal positivity was enhanced for items that received a think instruction only when participants had demonstrably learned the associated memory, but not when they had failed to learn the associated memory in the first place. For learned items that received a no-think instruction, the parietal ERPs where significantly reduced, suggesting that participants were successful in avoiding recollection of learned no-think items. However, parietal ERPs for items for which the participants had *failed* to learn the associate were also significantly more negative than learned think items, and not significantly different from ERPs for learned no-think items. This pattern is not well explained by differences in conflict/interference associated with the think or no-think instructions, as such generic task-related processes might be expected to be engaged irrespectively of the learning status of the associate. Instead, the results are better explained by parietal positivity indexing variable amounts of conscious recollection between the conditions: Parietal positivity was only enhanced when participants recollected learned items, but not when recollection failed because the items had never been successfully learned in the first place, or when recollection of learned items was voluntarily prevented.

Furthermore, the main effect of second half think/no-think instructions during the second half of presentations was larger and more reliable than the main effect of first half think/no-think instructions during the first half, consistent with participants' ratings that they were more successful at performing the task during the second half of presentations. This again suggests that the main effect of think/no-think instructions on parietal positivity from 450 msec onward was indexing the amount of recollected information rather than the amount of interference or conflict because interference/conflict accounts would predict the opposite pattern: ERP negativities should be more prominent when participants are having *less* success and *more* difficulty, that is, during the first half of presentations.[8] Nevertheless, an important objective of future research is to fully disentangle effects relating to interference/conflict from effects relating to recollection of individual items in ERP studies of recollection control. Employing a more sensitive measure of success at recollection control could be the key to achieve this: For example, by collecting individual estimates of success on a trial-by-trial basis, recollection control and interference/conflict accounts could be dissociated on a within-subjects basis, as they have opposite predictions for how parietal positivity should vary with success.

As described above, our results converge with earlier behavioral (Anderson & Green, 2001), fMRI (Depue et al., 2007; Anderson et al., 2004), and ERP evidence (Bergström et al., 2007; Fraser et al., 2007; Dzulkifli et al., 2006; Dzulkifli & Wilding, 2005; Herron & Wilding, 2005; Wilding et al., 2005; Herron & Rugg, 2003a, 2003b; Dywan et al., 1998, 2001, 2002) in suggesting that conscious recollection can be voluntarily controlled. The voluntary modulations of the parietal EM effect occurred specifically for items that participants were able to recall both when tested in the initial learning test prior to the think/no-think phase and in the final recall test following the think/no-think phase. It is therefore highly likely that participants would have been able to also recall these items during the think/no-think phase had they tried to do so, and that ERP differences during the think/no-think phase thus reflected voluntary processes at the time recollection or recollection avoidance occurred, rather than differences in forgetting between the think and no-think conditions (Anderson et al., 2004; Anderson & Green, 2001). Our results extend on previous research by suggesting that voluntary control over recollection is remarkably strong and flexible: Participants cannot only switch from recollection to avoiding recollection on an item-by-item basis but they can also switch from having repeatedly recalled a memory in response to a cue, to stopping recall of that memory when the instructions change, and vice versa. This indicates that even in situations when recollection is the highly practiced, automatic response to a retrieval cue, voluntary control processes can be recruited to override unwanted recollection.

Our experiment was only designed to investigate voluntary control of prepotent recollection, and not to address the further question of when, and if so how, avoiding prepotent recollection leads to subsequent enhanced forgetting (see Depue et al., 2007; Anderson et al., 2004 for discussions). Because we did not include a behavioral baseline condition, the current data cannot address whether or not recollection avoidance was achieved by an inhibitory mechanism that impaired the accessibility of avoided memories below baseline, as proposed in prior research (e.g., Anderson et al., 2004; Anderson & Green, 2001). However, the data do indicate that prepotent recollection can be successfully avoided without necessarily producing significant behavioral differences in later forgetting between repeatedly recalled and avoided memories. These results, together with our previous findings (Bergström et al., 2007), demonstrate how ERPs can be superior to behavioral measures when investigating voluntary control of recollection. Previous behavioral studies have sometimes failed to find enhanced forgetting of no-think items in the final cued recall test (e.g., Bulevich, Roediger, Balota, & Butler, 2006). 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 no-think items, and thereby show much more conclusively than those prior behavioral studies that participants were indeed successfully preventing recollection when asked to do so. Despite the nonsignificant differences in final recall performance, however, it is of course still possible that an inhibitory mechanism was involved in terminating recall of avoided memories in the current study, but without producing a lasting impairment strong enough to be measurable on the final test.[9]

Our research suggests an extension of the classical distinction between incidental and intentional recollection (e.g., Curran, 1999; Rugg et al., 1997; Schacter et al., 1996; Richardson-Klavehn & Gardiner, 1995; Richardson-Klavehn, Gardiner, et al., 1994; Moscovitch, 1992) by illustrating that voluntary control processes can be involved both in facilitating or stopping recollection, dependent on the current task goals. However, the results do not indicate that voluntary control can *always* override automatic recollection, as participants indicated that the avoided memories still intruded into consciousness on a smaller proportion of trials. There are likely to be certain types of memories that are too intrusive—at least initially—to be voluntarily avoided, and there are also likely to be individual differences in the ability to voluntarily avoid unwanted memories (Levy & Anderson, 2008). Therefore, future investigations are needed to establish these possible boundary conditions of voluntary control of recollection.

The overall effect of think/no-think instructions on the parietal EM effect correlated with self-reported ratings of withholding attention from the memory response so that the more participants reported actively resisting acknowledging or attending to the memory, the larger was the reduction of the parietal EM effect for no-think cues compared to think cues. This finding is of interest in the light of recent discussions regarding the nature of the parietal EM effect (e.g., Rugg & Curran, 2007; Vilberg, Moosavi, & Rugg, 2006; Wagner, Shannon, Kahn, & Buckner, 2005; Wilding, 2000). Despite the strong evidence linking the effect to conscious recollection, its precise functional significance is uncertain, and accumulating evidence suggests that it may reflect some aspect of the involvement of attention in episodic retrieval. One hypothesis is that the effect may reflect attentional orienting to internal MTL-dependent representations (see Wagner et al., 2005 for a discussion). However, a number of studies have shown that the parietal EM effect is sensitive to the *amount* of recollected information so that it is unlikely to represent a simple all-or-nothing attentional shift or signal (Vilberg et al., 2006; Wilding, 2000). Alternatively (e.g., Vilberg et al., 2006; Wagner et al., 2005), it may index processes that either support the representation of recollected information, such as an episodic memory buffer (Baddeley, 2000), or processes that act on such representations.

Our findings indicate that the size of the parietal EM effect is related to the amount of attentional resources allocated to memory representations, hence, is also related to the amount of episodic information held at the focus of attention or in the episodic memory buffer (Baddeley, 2000). It is generally agreed that only information at the focus of attention is available to consciousness (Velmans, 1996), and a crucial component of conscious recollection arguably involves allocating attentional resources to memories to-be-recollected (in fact, some view conscious retrieval as a form of internally directed attention; e.g., Anderson & Bjork, 1994). Voluntary control processes may be able to modulate whether recollection takes place or not by withholding attention from memory representations that would otherwise have become conscious through automatic MTL/hippocampal cue–trace interactions (Moscovitch, 1992). Such voluntary control may or may not also involve inhibition of the avoided memories (Depue et al., 2007; Anderson et al., 2004; Levy & Anderson, 2002; Anderson & Green, 2001). The suggestion that a strategic absence of a parietal EM effect for old items may reflect the absence of attention to products of cue–trace interactions has been made previously (Dzulkifli et al., 2006; Dzulkifli & Wilding, 2005; see also Dywan et al., 1998, 2001, 2002; for a related account). However, our results provide the first evidence of a relationship between a reduction of the parietal EM effect and participants self-reported experience of actively resisting attending to unwanted memories.

The current findings also have implications for practical applications of memory research in the legal domain, where brain activity tests for detecting deception have received increasing interest as alternatives to standard "lie-detector" tests measuring autonomic nervous system activity (e.g., Farwell & Donchin, 1991). These tests rely on measuring the brain activity correlates of recognition to detect whether suspects are remembering information during the test that only guilty persons would know. A crucial assumption of these tests is that memory-related brain activity is uncontrollably elicited by retrieval cues related to the concealed information. Previous research has shown that people can avoid detection in these brain activity tests by generating covert responses to all cue items, including those that are unrelated to the crime in question (Rosenfeld, Soskins, Bosh, & Ryan, 2004). Our results indicate a countermeasure not previously identified in this literature: Suspects may be able to train themselves to avoid recollection of incriminating knowledge to elude detection.

In conclusion, in both the first and second half of the test phase, ERPs showed a significantly reduced late parietal positivity when participants avoided recollection, demonstrating that reversing the instructions for some cues in the second phase had resulted in a within-item and within-participant reversal of the parietal EM effect. This effect was during the second phase modulated by an earlier emerging decrease in centro-parietal positivity specifically for the items that participants had previously repeatedly recalled, which therefore seems to index a process engaged when particularly intrusive memories have to be avoided. Our results replicate earlier findings (Bergström et al., 2007) which suggested that item-specific recollection of recollectable information can be avoided, but extend on those earlier results by showing that voluntary control over recollection is strong and flexible. Where previous research had indicated that people can recruit voluntary strategies to achieve recollection when automatic recollection fails to take place, we demonstrate that people can also recruit voluntary strategies to stop recollection of materials that would otherwise have been automatically recollected.

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Reprint requests should be sent to Zara Bergström, Department of Neurology II, Faculty of Medicine, Otto von Guericke University, Leipziger Str. 44, 39120 Magdeburg, Germany, or via e-mail: zara.bergstroem@med.ovgu.de.

Notes

1. If avoided items are more likely to be forgotten on the final test, this indicates that they were inhibited during the prior think/no-think phase (e.g., Anderson & Green, 2001). If items are successfully inhibited, avoiding recollection would require little voluntary effort, and a reduction of recollection-related ERP activity during no-think trials could be a consequence of successful inhibition, reflecting that inhibited items are no longer automatically recollected. Therefore, the issue of whether prepotent recollection can be voluntarily prevented is better examined without subsequent enhanced forgetting because without enhanced forgetting it is more likely that recollection remained the prepotent response throughout the think/no-think phase, and that any reduction of the parietal EM effect during no-think trials was achieved by effortful, voluntary control.
2. This experiment was not specifically designed for contrasting learned and not learned items because this issue was addressed in our prior study (Bergström et al., 2007), but the learning analysis allowed a direct verification of our conclusion that the parietal modulations were memory-specific. Because the current analysis split the EEG data into a larger number of ERP conditions than Bergström et al. (2007) and also had a higher initial learning rate, only a subset of 10 participants in the current study had sufficient trial numbers for adequate signal-to-noise ratio for the not-learned ERP conditions.
3. The complete results of the strategy questionnaire can be obtained from the authors on request. See also Levy and Anderson (2008) for further information on strategy distributions in the think/no-think task.
4. The bootstrap ratios of this contrast during the second half (not presented) show a markedly different pattern than the same contrast during the first half of presentations. During the second half, the two conditions with first half think instructions had more positive ERPs than the two conditions with first half no-think instructions across frontal sites from 800 msec until the end of the epoch, but there was no reliable effect of this contrast across parietal sites. Thus, there was no evidence that both the conditions with first half think instruction simply retained an increased parietal EM effect during the second half of presentations (only the T–T condition did, as those items where still presented with a think instruction; see Figure 6).
5. We did not use a measure of parietal positivity increase from the earlier (252–448 msec) to the later (452–548 msec) time window for this follow-up analysis, because as can be seen in Figure 7B, the specific ERP negativity for T–NT items in this subgroup was only apparent from around 400 msec post-stimulus. Analyzing the raw mean amplitudes between 452 and 548 msec was, therefore, deemed sufficient for the purpose of the follow-up analysis.
6. We thank an anonymous reviewer for this suggestion.
7. In addition, the parietal effect for items that were repeatedly recollected also responded in a way that is consistent with the view that this effect, in fact, indexes recollection. A correlate of recollection should be larger when the same items are repeatedly recollected because the magnitude of the parietal EM effect and the likelihood of recollection increase with repetition (e.g., Johnson, Kreiter, Russo, & Zhu, 1998). In the current study, items that were repeatedly presented with think instructions showed more positive parietal ERPs during the second than the first half of repetitions (we thank an anonymous reviewer for this observation).
8. In addition, the current results provide evidence that a specific strategy for recollection avoidance was particularly linked with a reduction of parietal positivity between 450 and 550 msec for no-think cues: the voluntary withholding of attentional resources from the to-be-avoided memory. If the think/no-think main effect on parietal positivity indexes a general conflict/interference response, it is unclear why it would correlate with such a specific memory control strategy. As we discuss later in this section, this relationship is of interest in the light of the recent discussion regarding the functional significance of the parietal EM effect.
9. The final recall test may have been rather insensitive because performance was at ceiling. However, there was a nonsignificant trend for lower final recall of items that were presented with no-think instructions during the first half of presentations than final recall of items presented with think instructions during the first half of presentations, suggesting that recollection avoidance during the first half may have impaired memory to some small degree. We thank an anonymous reviewer for this observation.

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