Research Report

An event-related potential investigation of the processing of Remember/Forget cues and item encoding in item-method directed forgetting

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ABSTRACT

This study examined the electrophysiological correlates of the processing of the Remember/Forget cues and the successful encoding of study items in item-method directed forgetting. Subjects engaged in an old/new recognition test and an item-method directed forgetting task. Event-related potentials (ERPs) time-locked to study items and Remember/Forget cues were compared according to the subsequent recognition performance. A reliable subsequent memory effect was elicited by the study items in the old/new recognition test. In contrast, the study items in the directed forgetting task did not yield reliable subsequent memory effects. Importantly, the Remember/Forget cues gave rise to ERPs that were predictive of the subsequent recognition performance to the study items preceding the cues. The subsequent memory effect elicited by the Remember cues was more sustained than that elicited by the Forget cues and showed distinct scalp distribution during the extended period. These results suggest that study items in the directed forgetting task are maintained in short-term memory with minimal further processing until the presentation of the Remember/Forget cues. In addition, the encoding mechanisms engaged by Remember cues and Forget cues are not entirely equivalent.

1. Introduction

Forgetting unwanted or irrelevant information is crucial for maintaining the functionality of memory. Intentional forgetting is often investigated with the directed forgetting paradigm, which instructs subjects to remember some study materials but to forget others (see Johnson, 1994; MacLeod, 1998, for reviews). In the item-method of directed forgetting, each study item is accompanied by a Remember cue or a Forget cue. These cues instruct subjects to remember or to forget on an item-by-item basis. A directed forgetting effect is obtained when items instructed to be forgotten (TBF) are less well remembered than items instructed to be remembered (TBR). It has been suggested that the item-method directed forgetting effect mainly results from the different processing of TBR and TBF items during encoding (e.g., Basden et al., 1993; Bjork, 1989; but see Ullsperger et al., 2000). In this study we recorded event-related potentials (ERPs) during the study...
phase of the item-method directed forgetting procedure to investigate the encoding processes related to the directed forgetting effect.

The differential rehearsal account for the directed forgetting effect proposes that TBR items received more rehearsal than TBF items (Bjork, 1970). Study items are initially maintained in short-term memory with rote rehearsal until the presentation of Remember/Forget cues. Rote rehearsal is terminated in response to a Forget cue, whereas elaborate rehearsal processes are allocated to the TBR items in response to a Remember cue. This view is supported by the finding that increasing the interval between study items and Remember/Forget cues has little effect on the recall of TBR and TBF items (Woodward and Bjork, 1971; Woodward et al., 1973). In addition, increasing the processing time of the Remember/Forget cues increases recollective experience for the recognition of TBR items but not TBF items (Gardiner et al., 1994). The differential rehearsal account, however, does not specify how TBF items are excluded from working memory (Taylor, 2005). The attentional inhibition account (Zacks et al., 1996) by contrast argues that following the presentation of the Forget cue, the TBF items become irrelevant information, subsequently inhibited actively and prevented from entering into working memory (Hasher and Zacks, 1988). This view is supported by the finding that older adults, who find it difficult to ignore TBF items, exhibited a smaller directed forgetting effect than young adults (Zacks et al., 1996). In addition, the instruction to forget was found to increase inhibition of return (Taylor, 2005); the way Forget cues discontinue memory encoding resembles the countermanding of a proponent response in a stop-signal paradigm (Hourihan and Taylor, 2006). However, there is also evidence suggesting that TBF items may not be actively inhibited, as TBR and TBF items elicited similar semantic priming effects (Marks and Dulaney, 2001).

The question of whether TBF items are actively suppressed or passively decayed relates to how well the TBF items are initially encoded and how effective the forget instruction is, both are important factors for the success of intentional forgetting (Johnson, 1994). A relevant issue of exploration is whether successfully remembered TBR and TBF items are encoded in different ways. Brain activities elicited by study items and Remember/Forget cues may shed light on these questions. Specifically, if Remember cues and Forget cues engage different processes, different brain activities should be observed. Moreover, the investigation of how brain activities elicited by study items and Remember/Forget cues relate to subsequent memory performance, the so-called subsequent memory effect (Paller et al., 1987; Rugg, 1995), should reveal whether the successful encoding of TBR and TBF items involves different mechanisms. Paller (1990) used word colors as Remember/Forget cues and found that the ERPs elicited by TBR items demonstrated greater initial positivity and subsequent negativity than TBF items. A similar finding was reported by Paz-Caballero and Menor (1999), who presented Remember/Forget cues after the offset of study items. These findings are consistent with the view that different processes are elicited by Remember and Forget cues. Paller (1990) also reported indistinguishable ERP subsequent memory effects for TBR and TBF items, suggesting similar mechanisms underlying the successful encoding of TBR and TBF items. However, the simultaneous presentation of study items and Remember/Forget cues (i.e., item colors) in Paller’s study made it difficult to differentiate between the encoding processes elicited by study items and those modulated by the Remember/Forget instructions. Paz-Caballero, Menor, and Jiménez (2004) reported that subjects who exhibited a large directed forgetting effect and those who demonstrated a smaller effect exhibited distinct patterns of ERP differences between Remember and Forget cues. However, Paz-Caballero et al. (2004) did not compare the subsequent memory effects associated with the Remember and Forget cues. It is therefore not clear whether the encoding processes elicited by the Remember and Forget cues are different.

To elucidate the nature of the directed forgetting effect, the subjects of the present work engaged in an old/new recognition test and two sessions of item-method directed forgetting task. ERPs were recorded in the study phase of both tasks. We attempted to test the following hypotheses: (1) if study items in the directed forgetting task are initially maintained with rote rehearsal, the subsequent memory effect elicited by the study items in the old/new recognition test should not be elicited by the study items in the directed forgetting task. In contrast, the ERPs elicited by the Remember/Forget cues should vary according to whether the study items immediately preceding the cues are subsequently recognized. (2) If the encoding of TBR and TBF items is of qualitatively different, the subsequent memory effect elicited by the Remember cues and Forget cues should differ, as different patterns of subsequent memory effects have been observed in deep and shallow encoding tasks. (Otten and Rugg, 2001).

2. Results

Repeated measures ANOVA was used to analyze the behavioral and ERP data. The Greenhouse–Geisser correction for non-sphericity was applied when necessary.

2.1. Behavioral results

Data from 6 subjects were discarded in the behavioral analysis because of their failure to complete all sessions of the experiment. The behavioral data of the remaining 21 subjects are displayed in Table 1. The correct rejection rates in the two tests did not differ significantly ($t_{20}=0.77, p=0.45$). A priori tests revealed that the hit rate to TBR items was significantly higher than the hit rate to TBF items ($t_{20}=7.12, p<0.001$). In addition, a one-way ANOVA on the hit rates to TBR and TBF items in the directed forgetting task and the hit rate in the old/new recognition test revealed a significant main effect ($F_{2,40}=29.48, p<.001$). Post-hoc comparisons with Bonferroni corrections showed that the hit rate to TBR items in the directed forgetting task was significantly higher than the hit rate in the old/new recognition test ($p=0.003$), which in turn was higher than the hit rate to TBF items in the directed forgetting task ($p=0.002$). To examine whether the two directed forgetting sessions exhibited different directed
forgetting effects, an ANOVA employing the factors of directed forgetting session and Remember/Forget instruction on the hit rates was conducted. The main effect of Remember/Forget instruction was significant ($F_{1,20}=51.9, p<.001$), reflecting the higher hit rate for TBR items than TBF items. The main effect of directed forgetting session and its interaction with Remember/Forget instruction were not significant ($F_{1,20}=0.34, p=.86$ and $F_{1,20}=0.98, p=.34$, respectively), revealing no evidence that the directed forgetting effect differed across the two sessions of directed forgetting test.

A one-way ANOVA on the response times associated with hits to TBR and TBF items in the directed forgetting task and hits in the old/new recognition task revealed a significant main effect ($F_{1,122,43}=5.1, p=0.03$). Post-hoc comparisons with Bonferroni corrections revealed that the response times on hits to TBR items were shorter than those associated with hits to TBF items in the directed forgetting task ($p<.001$) and hit trials in the old/new recognition task ($p=.04$). The response times for hits to TBF items and hits in the old/new recognition task did not differ from each other ($p=.73$). Another ANOVA employing the factors of directed forgetting session and Remember/Forget instruction on the RTs associated with hits to TBR and TBF items was conducted. The main effects of directed forgetting session and Remember/Forget instruction were both significant ($F_{1,20}=10.5, p=0.04$ and $F_{1,20}=29.39, p=0.001$, respectively), reflecting shorter RTs in the second session than the first session and for hits to TBR items than to TBF items. The interaction between directed forgetting session and Remember/Forget instruction was not significant ($F_{1,20}=2.39, p=0.137$).

### 2.2. ERPs recorded in the study phase of the old/new recognition test

ERPs elicited by the study words in the old/new recognition test were separately averaged for words that were subsequently correctly identified and subsequently incorrectly rejected (hereafter abbreviated to HIT_o/n and MISS_o/n respectively) based on data from 22 subjects who contributed more than 12 trials in each of the two subsequent response categories. The mean trial numbers (range in brackets) for these two categories were 58 (20–78) and 21 (12–39), respectively. Grand average ERP waveforms overlaid by these two conditions are displayed in Fig. 1A, which shows that the waveforms diverge about 300 ms after stimulus onset, with the ERPs for HIT_o/n being more positive than those for MISS_o/n. This positive-going subsequent memory effect was larger over the frontal and left scalp, and lasted until the end of the recording epoch.

ERPs were quantified by measuring the mean amplitudes of three time periods: 300–800, 800–1200, and 1200–1500 ms. The ANOVAs comparing the ERPs associated with HIT_o/n and MISS_o/n revealed that the main effect of subsequent response category was significant in the 300–800 ms and 800–1200 ms periods ($F_{1,21}=5.93, p=0.02$ and $F_{1,21}=8.37, p=0.01$, respectively), so was the interaction between subsequent response category and left-right scalp region ($F_{1,9, 39.4}=4.86, p=0.01$ and $F_{1,6, 34.2}=3.5, p=0.04$, respectively). Subsidiary analyses showed that the effect of subsequent response category was significant over the left scalp region (300–800 ms: $F_{1,21}=6.42, p=0.02$; 800–1200 ms: $F_{1,21}=6.8, p=0.02$) and medial scalp region (300–800 ms: $F_{1,21}=7.9, p=0.01$; 800–1200 ms: $F_{1,21}=11.94, p=0.002$) but not the right scalp region (300–800 ms: $F_{1,21}=1.74, p=0.2$; 800–1200 ms: $F_{1,21}=0.25, p=0.63$). The interaction between subsequent response category and anterior–posterior caudality was significant in all the three time periods (300–800 ms: $F_{1,9, 39.5}=3.67, p=0.04$; 800–1200 ms: $F_{2, 41.3}=5.93, p=0.006$; 1200–1500 ms: $F_{1,8, 38}=3.66, p=0.04$). Subsidiary analyses showed that the effect of subsequent response category was significant over the frontal polar sites (300–800 ms: $F_{1, 21}=11.65, p=0.003$; 800–1200 ms: $F_{1, 21}=16.31$,

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Response</th>
<th>Hit/correct rejection rate</th>
<th>Reaction time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old</td>
<td>Hit</td>
<td>0.73 (0.11)</td>
<td>1018 (190)</td>
</tr>
<tr>
<td></td>
<td>Miss</td>
<td>0.80 (0.12)</td>
<td>1141 (229)</td>
</tr>
<tr>
<td>New</td>
<td>CR</td>
<td>0.85 (0.08)</td>
<td>1060 (194)</td>
</tr>
<tr>
<td></td>
<td>FA</td>
<td>1.11 (0.34)</td>
<td>1142 (230)</td>
</tr>
</tbody>
</table>

### Table 1 – Mean reaction times (in milliseconds), hit rates, and correct rejection rates in the old/new recognition test and directed forgetting test (S.D. in parentheses)

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Response</th>
<th>Hit/correct rejection rate</th>
<th>Reaction time</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OLD_TBR</td>
<td>Hit</td>
<td>0.84 (0.11)</td>
<td>959 (186)</td>
</tr>
<tr>
<td></td>
<td>Miss</td>
<td>0.83 (0.10)</td>
<td>1095 (300)</td>
</tr>
<tr>
<td>OLD_TBF</td>
<td>Hit</td>
<td>0.61 (0.16)</td>
<td>1014 (204)</td>
</tr>
<tr>
<td></td>
<td>Miss</td>
<td>0.63 (0.18)</td>
<td>1064 (228)</td>
</tr>
<tr>
<td>New</td>
<td>CR</td>
<td>0.86 (0.09)</td>
<td>1098 (195)</td>
</tr>
<tr>
<td></td>
<td>FA</td>
<td>0.80 (0.11)</td>
<td>1114 (265)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Session</th>
<th>Old</th>
<th>Remember/Forget instruction</th>
<th>New</th>
<th>Remember/Forget instruction</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Overall</th>
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</tr>
</tbody>
</table>

One subject completed the old/new recognition test but did not attend the directed forgetting test. His data was therefore included in the analyses of ERP subsequent memory effect for old/new recognition test but not in the behavioral analyses.
p = .001; 1200–1500 ms: $F_{1,21} = 7.23, p = .01$) but not other scalp regions.

A topographical analysis employing the factors of time period (300–800, 800–1200, and 1200–1500 ms) and recording site (62 scalp electrodes) on the subsequent memory effect (i.e., subtracting Miss_o/n from Hit_o/n) found that the interaction between time period and recording site was not significant ($F_{7,6106.1} = 0.84, p = .57$), revealing no evidence that the distribution of the subsequent memory effect differed across the three time periods (see Fig. 1C).

### 2.3. ERPs recorded in the study phase of the directed forgetting task

#### 2.3.1. ERPs elicited by the items

ERPs elicited by the study words in the directed forgetting task, either followed by a Remember cue or a Forget cue, were separately averaged for words that were subsequently correctly identified and words that were subsequently incorrectly rejected based on data from 21 subjects who contributed sufficient (>12) trials in these two conditions. The mean trial numbers (range in brackets) for these two conditions were 97 (40–136) and 36 (12–65), respectively. Grand average ERP waveforms overlaid by these two conditions are displayed in Fig. 1B, which shows that the waveforms associated with these two classes of subsequent response categories were similar. ERPs were quantified by measuring the mean amplitudes of three time periods (300–800, 800–1200, and 1200–1500 ms) as in the analysis of the ERPs recorded in the study phase of the old/new recognition test. Statistical analyses showed that there were no significant effects involving the factor of subsequent response category in any of the three time periods.

#### 2.3.2. ERPs elicited by the Remember/Forget cues

ERPs elicited by the Remember and Forget cues were separately averaged according to whether the study words preceding these cues were subsequently correctly identified (hereafter abbreviated to HIT_df_rcue and HIT_df_fcue for R and F cues respectively) or incorrectly rejected (hereafter abbreviated to MISS_df_rcue and MISS_df_fcue for Remember and Forget cues respectively) based on data from 15 subjects who contributed more than 12 trials in all the four conditions. Table 2 displays the hit rates and correct rejection rates of the 15 subjects in the two sessions of directed forgetting test. As shown in the table, these 15 subjects gave rise to a reliable directed forgetting effect. The hit rate to TBR items was significantly higher than the hit rate to TBF items ($t_{14} = 6.15, p < .001$). An ANOVA employing the factors of directed forgetting session and Remember/Forgetting instructions on the hit rates showed that the interaction between these two factors was not significant ($F_{1,14} = 0.28, p = .6$), revealing no evidence that the directed forgetting effect differed across the two conditions.
directed forgetting sessions. The mean trial numbers (range in bracket) of the HIT_df_rcue, HIT_df_fcue, MISS_df_rcue, and MISS_df_fcue conditions were 52 (18–74), 35 (12–53), 15 (12–27) and 29 (12–51), respectively. Grand average ERP waveforms overlaid by HIT_df_rcue and MISS_df_rcue, as well as by HIT_df_fcue and MISS_df_fcue, are shown in Figs. 2A and B. As can be seen from the figures, the waveforms diverge about 200 ms after stimulus onset. The waveforms associated with Remember cues were more positive-going than those associated with Forget cues over posterior sites (see Fig. 3A).

ERPs were quantified by measuring the mean amplitudes of the 200–400, 400–500, and 600–900 ms time periods. The four conditions of interest in this analysis (i.e., HIT_df_rcue, HIT_df_fcue, MISS_df_rcue, and MISS_df_fcue) were categorized into two factors (Remember/Forget cue and subsequent response category), each with two levels (Remember cue vs. Forget cue and subsequent HIT vs. subsequent MISS, respectively) for statistical analysis.

The interaction between Remember/Forget cue and anterior–posterior caudality was significant ($F_{1.7,23.5}=5.93, p=.01$) in the 200–400 ms period. Subsidiary analyses showed that the effect of Remember/Forget cue was significant at posterior sites ($F_{1,14}=11.38, p=.005$), approached significance at

<p>| Table 2 – Hit rates and correct rejection rates in the directed forgetting test (S.D. in parentheses) of 15 subjects who were included in the ERP analysis for Remember and Forget cues |
|----------------------------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Directed forgetting test</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBR_HIT</td>
<td>0.81 (0.13)</td>
<td>0.78 (0.11)</td>
<td>0.79 (0.11)</td>
</tr>
<tr>
<td>TBF_HIT</td>
<td>0.55 (0.15)</td>
<td>0.55 (0.16)</td>
<td>0.55 (0.13)</td>
</tr>
<tr>
<td>New_CR</td>
<td>0.88 (0.07)</td>
<td>0.83 (0.09)</td>
<td>0.86 (0.07)</td>
</tr>
</tbody>
</table>

Starting from 400 ms after stimulus onset, however, the ERPs elicited by the Forget cues were more positive-going than those elicited by the Remember cues over the anterior scalp region. In respect to the subsequent memory effect elicited by the Remember/Forget cues (see Fig. 4A), the waveforms were more positive-going when the study words preceding the cues, either Remember or Forget, were subsequently correctly identified in comparison to when the preceding words were subsequently incorrectly rejected.

ERPs were quantified by measuring the mean amplitudes of the 200–400, 400–500, and 600–900 ms time periods. The four conditions of interest in this analysis (i.e., HIT_df_rcue, HIT_df_fcue, MISS_df_rcue, and MISS_df_fcue) were categorized into two factors (Remember/Forget cue and subsequent response category), each with two levels (Remember cue vs. Forget cue and subsequent HIT vs. subsequent MISS, respectively) for statistical analysis.

The interaction between Remember/Forget cue and anterior–posterior caudality was significant ($F_{1.7,23.5}=5.93, p=.01$) in the 200–400 ms period. Subsidiary analyses showed that the effect of Remember/Forget cue was significant at posterior sites ($F_{1,14}=11.38, p=.005$), approached significance at

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Fig. 2 – (A) ERP waveforms elicited by the Remember cue, averaged on the basis of subsequent memory performance to the study words preceding the cues. Hit_df_rcue: the study word preceding the Remember cue was subsequently correctly identified. Miss_df_rcue: the study word preceding the Remember cue was subsequently incorrectly rejected. (B) ERP waveforms elicited by the Forget cue, averaged on the basis of subsequent memory performance to the study words preceding the cues. Hit_df_fcue: the study word preceding the Forget cue was subsequently correctly identified. Miss_df_fcue: the study word preceding the Forget cue was subsequently incorrectly rejected. (C) Voltage spline maps showing the topographies of the subsequent memory effects elicited by the Remember cues. (D) Voltage spline maps showing the topographies of the subsequent memory effects elicited by the Forget cues.
central sites \((F_{1,14}=4.22, p=.06)\), but was not significant at anterior sites \((F_{1,14}=1.15, p=.3)\) and frontal polar sites \((F_{1,14}=0.24, p=.64)\). These results reflect the positive-going effect associated with Remember cues as opposed to Forget cues over the posterior scalp. The interaction between Remember/Forget cue and anterior–posterior caudality was also significant \((F_{1.6,22.3}=12.09, p=.001)\) in the 400–500 ms period. Follow-up analyses showed that in comparison to Forget cues, the waveforms associated with Remember cues were more negative-going over the anterior scalp region \((F_{1,14}=4.68, p=.04)\) but more positive-going over the posterior scalp region \((F_{1,14}=8.98, p=.01)\). A topographical analysis on the Remember/Forget cue effects (i.e., subtracting the ERPs elicited by the Forget cues from the ERPs elicited by the Remember cues) in the 200–400 ms and 400–500 ms periods revealed a significant interaction between time period and recording electrode sites \((F_{3.1,43.6}=3.71, p=.02)\). This interaction confirms that the scalp distributions of the Remember/Forget cue effect (see Fig. 3B) differed in the two time periods.

The main effect of subsequent response category was significant in the 200–400 ms and 400–500 ms periods \((F_{1,14}=9.92, p=.007 \text{ and } F_{1,14}=5.55, p=.03, \text{ respectively})\). The interaction between subsequent response category and left–right scalp region was significant in the 200–400 ms period \((F_{1.8,25.4}=3.75, p=.04)\). Follow-up analyses showed that the effect of subsequent response category was significant over the medial scalp region \((F_{1,14}=11.71, p=.004)\) and right scalp region \((F_{1,14}=12.17, p=.004)\). These results suggest that the ERPs elicited by the Remember/Forget Cues were more positive-going over medial and right scalp regions when the preceding study words were subsequently remembered than when they were subsequently forgotten. A topographical analysis employing the factors of time period (200–400 and 400–500 ms) and recording site (62 scalp electrodes) on the subsequent memory effect elicited by Remember/Forget cues (i.e., subtracting subsequent MISS from subsequent HIT) found that the interaction between time period and recording site was not significant \((F_{3.7,52.2}=2.27, p=.09)\), revealing no evidence that the distribution of the subsequent memory effect elicited by the Remember/Forget cues differed in the two time periods (see Fig. 4B). Topographical analyses comparing the scalp distribution of the subsequent memory effect elicited by the Remember/Forget cues in the directed forgetting task during the 200–500 ms period and the distributions of the subsequent memory effect elicited by the study items in the old/new recognition test during the 300–800, 800–1200, and 1200–1500 ms periods (see Fig. 1C) were also conducted. The interaction between experiment and recording site was significant \((300–800 \text{ ms}: F_{3.5,48.5}=3.47, p=.02; 800–1200 \text{ ms}: F_{5.7,79.2}=2.55, p=.03; 1200–1500 \text{ ms}: F_{6,83.7}=3.55, p=.005)\).

**Fig. 3** – (A) ERP waveforms elicited by the Remember cue (red line) and Forget cue (black line) at midline sites. (B) Voltage spline maps showing the topographies of the Remember/Forget cue effect (the difference between the ERPs elicited by the Remember cues and Forget cues) in the 200–400 ms and 400–500 ms time periods.

**Fig. 4** – (A) ERP waveforms elicited by the Remember/Forget cues at midline sites, averaged across Remember cues and Forget cues on the basis of subsequent recognition performance to the study words preceding the cues. Subsequent Hit: the study words preceding the Remember/Forget cues were subsequently correctly identified. Subsequent Miss: the study words preceding the Remember/Forget cues were subsequently incorrectly rejected. (B) Voltage spline maps showing the topographies of the subsequent memory effects elicited by the Remember/Forget cues in the 200–400 ms and 400–500 ms time periods.
indicating that the distributions of the subsequent memory effects elicited by the study items in the old/new recognition test and the Remember/Forget cues in the directed forgetting task differed from each other.

The interaction between Remember/Forget cue and subsequent response category was not significant in 200–400 and 400–500 ms, nor was any other interaction effect involving these two factors. However, there was a significant three-way interaction between Remember/Forget cue, subsequent response category, and anterior–posterior caudality in the 600–900 ms period (F1,1,15.9 = 4.56, p = .04). Subsidiary analyses showed that the interaction between subsequent response category and Remember/Forget cue was significant over the posterior scalp region (F1,14 = 4.26, p = .05), reflecting a significant effect of subsequent response category for Remember cues (F1,14 = 5.29, p = .04) but not for Forget cues (F1,14 = 1.42, p = .25). Topography analyses on the subsequent memory effects elicited by the Remember cues and Forget cues during the 200–400 and 400–500 ms periods showed that the interaction between Remember/Forget cue and recording site was not significant (200–400 ms: F3,7,51.8 = 0.47, p = .74; 400–500 ms: F4.7,65.4 = 1.06, p = .39), revealing no evidence that the scalp distributions of the subsequent memory effects elicited by the two types of cues differed from each other. The topography of the subsequent memory effect elicited by the Remember cue during the 600–900 ms period, however, differed from the topography of the subsequent memory effect elicited by the Remember/Forget cues during the 200–500 ms period (F6,3,88.6 = 2.44, p = .03).

3. Discussion

A directed forgetting effect was revealed in the behavioral data: the hit rate for TBR items was higher than that for TBF items. Additionally, the hit rate in the old/new recognition test was lower than the recognition rate for TBF items in the directed forgetting task, but higher than that for TBF items. Differences in recognition performance may result from interference caused by an increased number of items to be remembered in the old/new recognition test comparative to the directed forgetting task. Alternatively, the encoding processes used in the directed forgetting task for TBR and TBF items may have differed from those used for study items in the old/new recognition test. Behavioral data in the current study cannot be used to differentiate between these two possibilities. However, the ERPs recorded in the study phase may shed some light on this issue.

3.1. The ERPs elicited by the study items

A reliable subsequent memory effect was observed in the old/new recognition test. The ERPs were more positive-going for study items that were subsequently correctly identified in comparison to those incorrectly rejected. This finding resembles the subsequent memory effects observed in previous studies (e.g., Fabiani et al., 1990; Mangles et al., 2001; Paller et al., 1987; Weyerts et al., 1997) although the effect observed here was more extensive in duration and lateralized to the left hemisphere. The subsequent memory effect observed indicates that cognitive operations leading to successful encoding are revealed in the electrophysiological data in the current study. In sharp contrast, the study items in the directed forgetting task did not give rise to reliable subsequent memory effects. The ERPs elicited by the study items were statistically indistinguishable whether or not they were subsequently remembered. Instead, it was the Remember/Forget cues that elicited ERPs predictive of the later recognition performance to the study items.

There are several possible interpretations of why study items in the directed forgetting test did not give rise to reliable subsequent memory effects. First, the null result could be due to the lack of statistical power, possibly because of insufficient subjects and trials. Second, all study items, including those being incorrectly rejected in the subsequent recognition memory test, were successfully encoded and maintained in short-term memory before the presentation of the Remember/Forget cues. There were no reliable subsequent memory effects simply because no items were forgotten during this time period. Third, some study items did fail to be encoded and maintained in short-term memory. Nevertheless the ERPs were not sensitive to the processes that are related to successful encoding/maintenance prior to the Remember/Forget cues. The first interpretation could be tentatively ruled out because of the following reasons. The numbers of subjects and trials included in the analyses of study items were comparable in the old/new recognition and directed forgetting tests. The study items in the old/new recognition test, however, gave rise to robust subsequent memory effects. In addition, the analyses of the ERPs elicited by the Remember/Forget cues, which included relatively fewer subjects and trials, gave rise to reliable subsequent memory effects. The absence of subsequent memory effects for the study items in the directed forgetting test therefore cannot be exclusively attributed to the lack of statistical power. In regard of the other two interpretations, the current study cannot be used to differentiate between them. Nonetheless, whichever of the two holds, the data lend support to the view that study items in the item-method directed forgetting task were maintained in short-term memory with minimal further processing until the presentation of Remember/Forget cues. The cognitive operations leading to successful encoding revealed in the old/new recognition test were extensively attenuated in the directed forgetting test. If the third interpretation is valid, the data suggest that the processes of maintaining study items in memory are different from the encoding processes involved in non-semantic shallow encoding tasks. Reliable subsequent memory effects have been reported in studies employing shallow encoding tasks, although these effects were of smaller magnitudes or different topographical distribution in comparison to the subsequent memory effects observed in deep encoding tasks (e.g., Friedman et al., 1996; Otten and Rugg, 2001). The absence of subsequent memory effects here suggests that the maintenance of study items in the directed forgetting task may involve automatic operations elicited by the individual items. These operations however do not contribute to the subsequent memory effects observed in shallow encoding tasks.

2 We thank an anonymous reviewer for raising this point.
One question that follows is whether the cognitive operations underlying the successful encoding of study items in the old/new recognition test are identical to those elicited by the Remember/Forget cues in the directed forgetting task. The comparison of the subsequent memory effects in the two tests suggests that this may not be the case. The duration of the subsequent memory effect is longer for the old/new recognition test than the directed forgetting task. Furthermore, the scalp distribution of the subsequent memory effect was left-lateralized for the old/new recognition test and right-lateralized for the directed forgetting task (see Fig. 1C and Fig. 3B). The different scalp distributions between these two subsequent memory effects reveal that the encoding processes in the two tasks do not fully overlap. In conjunction with the shorter duration of the subsequent memory effect in the directed forgetting task versus that in the old/new recognition test, our findings suggest that some efficient encoding processes were elicited by the Remember/Forget cues.

3.2. The ERPs elicited by the Remember/Forget cues

The Remember/Forget cues may serve as triggers to deploy attention resources onto items that are maintained in short-term memory with rote rehearsal. This conjecture gains support from the finding that the ERPs associated with Remember cues were more positive-going than those associated with Forget cues over the posterior scalp regions during 200–500 ms after stimulus onset. This positive-going effect associated with the Remember cues has been reported in previous studies (Paller, 1990; Paz-Caballero et al., 2004; Paz-Caballero and Menor, 1999). Given its latency and scalp distribution, this positive-going effect resembles the P300 or P3b effect which has been linked with attention allocation (Kok, 2001) and related to memory encoding (Azizian and Polich, 2007; Fabiani and Donchin, 1995; Polich, 2007). Our interpretation for this P300-like effect is that the Remember cues and Forget cues relate their preceding study items to the encoding task with different degrees of relevance. Both types of cues provide information about how study items held in short-term memory should be processed. However, the Remember cues rendered the study items in short-term memory relevant to the encoding task, the Forget cues dissociated the two. The "targetness" endowed to the study items by the Remember cues led to the deployment of attention resources onto the study items. Following the P300-like effect, there was a positive-going effect associated with the Forget cues relative to the Remember cues over the frontal scalp region. This positive-going effect differs in scalp distribution from the P300-like effect associated with the Remember cues (see Fig. 3B), and has been suggested by Paz-Caballero et al. (2004) to reflect some inhibitory process on the items to be forgotten.

3.3. The subsequent memory effect elicited by the Remember/Forget cues

One primary question this study explored was whether the successful encoding of TBR and TBF items involved different processes. This issue was investigated by examining the subsequent memory effects elicited by Remember cues and Forget cues. If the encoding operations elicited by these two types of cues differ, different patterns of subsequent memory effects should be elicited. We found that the subsequent memory effect elicited by Remember cues was more sustained in duration than the effect elicited by Forget cues. This finding suggests that the encoding mechanisms engaged by the Remember/Forget cues operated more extensively for Remember cues than Forget cues. Additionally, the subsequent memory effect elicited by the Remember cues during the extended time period (600–900 ms) and the effect elicited by the Remember/Forget cues during the earlier time period (200–500 ms) gave rise to different scalp distributions. The Remember cues therefore may have elicited some encoding mechanisms that were not engaged by the Forget cues. In a recent fMRI study, Wylie et al. (2008) reported an interaction effect between Remember/Forget instruction and subsequent memory outcome on several memory-related areas. They noted that the right inferior prefrontal gyrus (BA47) was strongly activated when TBF items were subsequently successfully forgotten. The present work on the other hand revealed encoding operations that are engaged by Remember cues but not by Forget cues. In conjunction with the finding that Remember and Forget cues elicited indistinguishable subsequent memory effects during the early time period (200–500 ms), our findings suggest that initially both types of cues engaged similar encoding mechanisms. The TBF items, however, are prevented from engaging some further encoding operations, which are specifically engaged by Remember cues. A similar interpretation was proposed by Wylie et al. (2008) for the greater activation in superior frontal gyrus (BA10/11) when TBF items were successfully forgotten comparative to when TBR items were unintentionally forgotten in the subsequent test. Wylie et al. suggested that the frontal area may be involved in preventing unwanted information from being encoded. In the present work, the frontal distributed positivity associated with Forget cues could be related to the act of preventing TBF items from being further processed. The subsequent memory effect specifically elicited by Remember cues was observed in a time period (600–900 ms) later than the time at which the positivity associated with Forget cues was observed (400–500 ms). This difference in timing could reflect that the further encoding operations were not engaged by the Remember cues until the processes that prevent TBF items from being further processed were initiated. One caveat for this argument is that the onset of ERP effects only reveals the “upper bound” on time at which different processes are engaged (Rugg and Coles, 1995). The indistinguishable subsequent memory effects for Remember cues and Forget cues during the 200–500 ms period could result from the insufficiency of statistical power to detect the difference. However, this consideration should not temper the conclusion that some further encoding operations were not engaged by the Forget cues.

One question that follows is how the further encoding operations engaged by Remember cues relates to the directed forgetting effect. Previous studies have shown not only quantitative but also qualitative differences between the recollection of TBR and TBF items. When the Remember/
Know procedure (Tulving, 1985) was employed in the directed forgetting task, TBR items received more Remember responses than TBF items did (Gardiner et al., 1994; Lee et al., 2007; Sonntag et al., 2003). When ERPs were recorded during the test phase, TBR items elicited the parietal old/new effect, an effect that has been linked to recollection-based recognition (see Rugg and Curran, 2007 for a recent review of ERP old/new effects). The parietal old/new effect, however, was absent or relatively small for TBF items (Paz-Caballero and Menor, 1999; Ullsperger et al., 2000). These findings indicate that recollection was elicited by TBR items but was not, or only weakly, elicited by TBF items at test. The present work did not include measures that can differentiate between subjective experiences associated with the recognition of TBR and TBF items. However, the analyses of ERPs recorded during the test phase (not reported here) also showed a greater parietal old/new effect for TBR items than TBF items. Based on these findings, a plausible conjecture is that the further encoding operations engaged by Remember cues are related to the subsequent greater recollective experience associated with TBR items comparative to TBF items. A relevant issue is whether the subsequent memory effect specifically elicited by the Remember cues, given its latency and scalp distribution, is a manifestation of the P3b wave. Previous studies have shown that the amplitude of P3b elicited by study items that are isolated from others is correlated with subsequent memory performance of these items (e.g., Fabiani et al., 1990; Karis et al., 1984). An interpretation for this finding is that the encoding of isolated items requires changes of the current model of the context and memory reorganization. The representations of the isolated items in memory are therefore distinct and stand out from others (Fabiani and Donchin, 1995). Study items in the present work presumably were not different or isolated from each other prior to the Remember/Forget cues. The presentation of Remember cues, however, could render the TBR items distinctive and their representations marked. It is therefore possible that the subsequent memory effect specifically elicited by the Remember cues reflects the relationship between P3b and memory encoding. However, previous studies showed that this relationship holds only when subjects used rote rehearsal but not when they employed elaborative strategies for memorization (Fabiani et al., 1990). If the further encoding operations engaged by Remember cues, as noted above, are elaborative processing that leads to recollection in the later test, the subsequent memory effect specifically elicited by Remember cues and the P3b wave may not be entirely equivalent. Encoding operations unrelated to context updating may have contributed to this subsequent memory effect.

3.4. Implications for the item-method directed forgetting effect

As mentioned in the Introduction, the item-method directed forgetting effect is generally attributed to the differential rehearsal of TBR and TBF items. However, very few studies examined encoding-related brain activities to investigate how study items are processed prior to the presentation of Remember/Forget instructions and whether the rehearsals for TBR and TBF items are of quantitative or qualitative differences. In the present work, the absence of subsequent memory effects for study items in the directed forgetting test provides electrophysiological evidence that maintaining items in short-term memory with rote rehearsal has limited contribution to the directed forgetting effect. At least, the encoding mechanisms reflected by the subsequent memory effects in the old/new recognition test are not in operation for study items in item-method directed forgetting. On the other hand, the finding that there are encoding operations engaged by Remember cues but not by Forget cues suggests that the rehearsals for TBR and TBF items are of qualitative difference. This idea has been implicated in studies employing measures additional to old/new judgments during the retrieval stage, such as subjective reports (Gardiner et al., 1994; Lee et al., 2007; Sonntag et al., 2003) and ERP old/new effects (Paz-Caballero and Menor, 1999; Ullsperger et al., 2000). The current study provided direct evidence that TBR items are not only more rehearsed but are also more elaborated than TBF items.

Whether the present findings support the claim that inhibition is involved in item-method directed forgetting may depend on how inhibition is defined. The current study may not speak much about whether the representations of TBF items are inhibited, as there were no appropriate measures for this concept of inhibition. However, consider the findings of indistinguishable subsequent memory effects for Remember and Forget cues during the early time period, and that Remember cues elicited a more sustained and distinct subsequent memory effect. They suggest that some similar encoding processes were engaged by both types of cues but were stopped for TBF items later. TBF items were prevented from engaging further encoding mechanisms. In consideration of MacLeod’s definition of cognitive inhibition: “the stopping or overriding of a mental process, in whole or in part, with or without intention” (MacLeod, 2007, p.5), the current findings may have revealed the role of inhibition in directed forgetting as the prevention of TBF items from being further processed.

4. Concluding remarks

We have demonstrated that Remember/Forget cues elicited a reliable subsequent memory effect in the item-method directed forgetting task, and that their preceding study items comparatively elicited no such effect. This result indicates that study items are maintained in short-term memory with rote rehearsal until the presence of the Remember/Forget cues. The subsequent memory effect elicited by the Remember/Forget cues differed from the effect elicited by the study items in old/new recognition, suggesting that encoding mechanisms in these two tasks are dissociable.

In addition, the subsequent memory effect elicited by the Remember cues was more sustained than that elicited by the Forget cues and showed distinct scalp distribution during the extended period. We conclude that processes involved in the successful encoding of TBR and TBF items are not entirely equivalent. Further studies are needed to examine whether and how inhibition processes modulated these encoding processes.
5. Experimental procedures

5.1. Participants

A total of 27 undergraduate students from National Central University were recruited. All these participants were right-handed native Mandarin Chinese speakers with normal or corrected-to-normal vision. They were paid at the rate of 250 New Taiwan Dollars per hour.

5.2. Materials

Stimuli consisted of 600 Chinese two-character nouns. These 600 words were divided into three experimental lists of 200 words, which were then assigned to one session of old/new recognition test and two sessions of directed forgetting test respectively. For all the three lists, 100 words were presented at study and served as old items in the following test while the other 100 words were not shown at study and served as new items in the following test. For the two lists assigned to the directed forgetting sessions, half of the study words were followed by the Remember cue and the other half were followed by the Forget cue. Across the two sessions of directed forgetting test, there were 100 study words followed by the Remember cue, 100 study words followed by the Forget cue, and 200 unstudied new words. The allocation of the three lists to the three sessions and the assignments of the words as study words in the old/new recognition, study words in the directed forgetting test followed by Remember or Forget cues, and as new words were counterbalanced across subjects. The presentation orders of the study words and test words were randomly assigned for each subject. Maximum vertical and horizontal visual angles of the words on the screen were approximately 1° and 2° respectively.

5.3. Procedures

Subjects visited our laboratory twice — during the first visit, they participated in one session of old/new recognition testing; during the second, they participated in two sessions of directed forgetting testing. The two visits were on average separated by 7 days. Subjects were in both visits fitted with an elastic electrode cap and then seated at a viewing distance of 80 cm away from a monitor. In the study phase of the old/new recognition test, each trial started with the fixation character “+” for 500 ms followed by the study word. The study word was presented for 500 ms, after which the second fixation character “−” was shown for 1500 ms. Subjects were instructed to memorize all the study words regardless of whether they had been followed by an R or an F cue in the study phase. To ensure that subjects followed the Remember/Forget instructions in both sessions of the directed forgetting task, the subjects were told following the first study phase that the preceding presentation of Remember/Forget cues was a procedural error committed by the experimenter, and that they should in fact be presented in the next list. The subjects were requested to make an “old” response for all studied items in the coming recognition test, and to follow the Remember/Forget instructions in the subsequent study phase.

5.4. ERP recording

ERPs were recorded during the study and test phases, but only data recorded in the study phase are reported here. Subjects were fitted with an ERP recording cap (Quick-Cap) prior to the experiment. EEG was continuously recorded from 64 silver/silver chloride electrodes, 62 of which are embedded in an elastic cap. The remaining two electrodes were placed on the right and left mastoids. All channels were referenced to a channel located between Fz and FCz, and were re-referenced off-line to represent recordings with respect to linked mastoids. Vertical and horizontal EOG were recorded bipolarly from electrodes placed above and below the right eye, and on the outer canthi of each eye respectively. Data were sampled at a rate of 4 ms per point and digitized with 24-bit resolution. All channels were amplified with a bandpass of 0.03–70 Hz (3 dB points).

5.5. ERP analysis

ERPs were computed for epochs of 1700 ms beginning 200 ms prior to stimulus onset. Linear regression was used to estimate and correct the contribution of blink artifact to the EEG. Trials containing horizontal eye movement, non-blink vertical eye movement, A/D saturation, or with a baseline drift exceeding 70 μV in any channel, were rejected. A low pass filter with cutoff frequency at 30 Hz was applied to the epoched data. Averaging of ERPs was performed separately for conditions of interest in the study phase of the two memory tests. ERPs were quantified by measuring the mean amplitudes of various time periods in the study phase, as stated in the result section. The time periods, which were chosen based on visual inspection and preliminary analyses of consecutive 100-ms latency intervals, show maximal differences between the waveforms. An ANOVA was first conducted for each time period on the data from 30 electrode sites. These sites were located over backward counting task. The test trials started with the presentation of the fixation character “+” for 500 ms, followed by the presentation of the test word. The test word was shown for 500 ms, after which the second fixation character “−” was shown for 1500 ms. Subjects made old/new judgments in response to the presentation of each test word. Responses were made by pressing one of two response keys with the index finger of each hand. The mapping of the hand to response category (old vs. new) was counterbalanced across subjects. In the directed forgetting test, subjects were instructed to make old responses for all studied words regardless of whether they had been followed by an R or an F cue in the study phase. To ensure that subjects followed the Remember/Forget instructions in both sessions of the directed forgetting task, the subjects were told following the first study phase that the preceding presentation of Remember/Forget cues was a procedural error committed by the experimenter, and that they should in fact be presented in the next list. The subjects were requested to make an “old” response for all studied items in the coming recognition test, and to follow the Remember/Forget instructions in the subsequent study phase.
twelve scalp regions: left frontal polar (FP1), medial frontal polar (FP2), right frontal polar (FP2), left anterior (F7, F5, F3), medial anterior (F1, F3, F2), right anterior (F4, F6, F8), left central (T7, C5, C3), medial-central (C1, Cz, C2), right central (C4, C6, T8), left posterior (P7, P5, P3), medial-posterior (P1, Pz, P2), and right posterior (P4, P7, P8). Factors entered into the ANOVA were condition of interest (see the Results section), left–right scalp region (left, medial, right), and anterior–posterior causality (frontal polar, anterior, central, and posterior). Subsidiary ANOVAs for pairwise comparison were conducted when there were significant effects involving condition of interest. When necessary, topographical analyses were conducted to compare the scalp distributions of the ERP differences across conditions. Prior to topographical analysis, the data from the 62 scalp electrode sites were range-normalized with the max method to avoid the confounding between any differences in the magnitudes of the two effects and the differences in scalp distribution (McCarthy and Wood, 1985). The range-normalized data were then entered as a factor with 62 levels (i.e., all the scalp electrodes) into the topographical analyses.

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