Intentional forgetting might be more effortful than remembering: An ERP study of item-method directed forgetting

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\textbf{ABSTRACT}

This study recorded ERPs while participants engaged in a procedure that combined semantic priming and item-method directed forgetting, aiming to investigate the issues of whether intentional forgetting demands cognitive efforts and modulates the semantic processing of to-be-remembered (TBR) and to-be-forgotten (TBF) items. Participants made lexical decisions to semantically related or unrelated prime and target words. A Remember/Forget cue, presented between the prime and target, designated the prime as TBR or TBF. When the cues were shown for 500 ms, targets preceded by Forget cues yielded a smaller P200 wave than those preceded by Remember cues. Furthermore, the topography of the N400 effect was different for targets preceded by Remember and Forget cues. The cues did not modulate the ERPs of the targets when they were shown for 1500 ms. Because P200 is sensitive to attention influence and the N400 effect reflects semantic processing, we conclude that forgetting is more effortful than remembering and that the semantic processing is different for TBR and TBF items. Nevertheless, there is a temporal limitation for the Remember/Forget cues to modulate the semantic processing and attentional resources in item-method directed forgetting.

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1. Introduction

In the item-method of directed forgetting, each study item is accompanied by a cue that instructs participants to remember or to forget on a trial-by-trial basis. Items that have been instructed to be forgotten (TBF) are in general less well remembered than those that have been instructed to be remembered (TBR), whether the subsequent memory test is recognition or recall (Basden et al., 1993). An obvious interpretation for the “item-method directed forgetting effect” emphasizes the different encoding of TBR and TBF items (e.g., Basden et al., 1993; Bjork, 1989; but see Ullsperger et al., 2000). TBF items receive only maintenance rehearsals that take place prior to the presentation of the Remember/Forget cues. TBR items, by contrast, receive additional elaborative rehearsals following the presentation of the Remember cue (Gardiner et al., 1994; Hsieh et al., 2009; Woodward and Bjork, 1971; Woodward et al., 1973).

In addition to the differential rehearsals, it has been suggested that the item-method directed forgetting effect also receives contributions from the active inhibition of TBF items following the presentation of the Forget cues (Fawcett and Taylor, 2008; Hasher and Zacks, 1988; Hourihan and Taylor, 2006; Taylor, 2005; Zacks et al., 1996). In an attempt to verify this suggestion, Marks and Dulaney (2001) incorporated the paradigm of semantic priming into item-method directed forgetting. Participants in their study made lexical decisions to target words that were each preceded by a semantically related or unrelated prime word. A Remember/Forget cue, presented between the prime and target items, instructed the participants to remember or to forget the preceding prime word. It was argued that TBF primes would elicit a reduced or even negative semantic priming effect if these items had been actively inhibited. Marks and Dulaney nonetheless found that the semantic priming effect was not modified by whether the primes were TBR or TBF. This finding, in addition to casting doubts on the claim that TBF items are actively inhibited, was also inconsistent with the view that TBF items receive more elaborative rehearsals than TBF items. Previous studies have shown that the magnitude of semantic priming effect varies as a function of the processing depth of the prime item (e.g., Chwilla et al., 1995; Smith, 1979; Smith et al., 1983). If TBR items are processed more elaboratively than TBF items, the
difference in processing depth should be manifested in the semantic priming effect.

The null effect of Remember/Forget cues on the reaction-time semantic priming effect, however, does not necessarily implicate equivalent semantic processing of TBR and TBF items. Semantic priming effect could be subserved by multiple mechanisms, including automatic spreading activation and strategically controlled processes of expectancy priming and semantic matching/integration (Neely, 1991). The semantic priming effects elicited by the TBR and TBF primes could involve non-equivalent mechanisms, between which the measurement of reaction time was not of sufficient sensitivity to differentiate (Heil et al., 2004; Neely and Kahan, 2001; Rolke et al., 2001). To address this issue, the current study incorporated the recording of event-related potentials (ERPs) into the paradigm of Marks and Dunaney (2001). We used the N400 effect (Kutas and Hillyard, 1980) elicited by the target items as an index to examine whether TBR and TBF primes were processed to different levels of representations. The N400 wave, a negative ERP deflection peaking at around 400 ms after stimulus onset with a maximum over the central-parietal scalp, is known to be sensitive the processing of semantics. The magnitude of the N400 wave has been found to be inversely related to the congruity between the eliciting stimulus and its preceding semantic context, whether the context is a single word or a sentence (Kutas and Federmeier, 2000; Kutas and Van Petten, 1994). In addition, the scalp distribution of the N400 effect has been found to differ when the eliciting items engaged different semantic networks or processes (e.g., Antal et al., 2000; Kiefer, 2001, 2005; Kounios and Holcomb, 1994; Naito et al., 2002). Therefore, if the semantic context provided by the primes and hence their integration with the targets are modulated by the Remember/Forget cues, such modulation should be reflected by the N400 effects elicited by the targets. Another possible reason why the semantic priming effect was equivalent for targets following Remember and Forget cues is that the incorporation of lexical decision judgments might have decreased levels of engagement on the mnemonic instructions. Based on previous findings that monetary incentives delivered at study could enhance subsequent memory performance (e.g., Adcock et al., 2006; Shigemune et al., 2010), we told participants prior to the lexical decision task that there would be bonus and penalty, respectively, for each of the TBR and TBF prime words recalled in the subsequent test. It was expected that this instruction would encourage the participants to follow the Remember/Forget instructions delivered during the study phase.

In addition to the semantic priming effect, Marks and Dunaney (2001) reported a longer lexical decision time for targets preceded by Remember cues than those that were preceded by Forget cues, irrespective of the prime–target relationship. They interpreted this finding as reflecting the great attentional resource allocated to TBR primes, which resulted in an effortful switch from an encoding mode to a retrieval mode for making lexical decisions to targets. This interpretation contrasts with a recent study (Fawcett and Taylor, 2008) that integrated a probe detection task into directed forgetting. Fawcett and Taylor manipulated the stimulus onset asynchrony (SOA) between the Remember/Forget cues and probes. They found that in the short SOA conditions, the detection time was longer for probes preceded by Forget cues than those that were preceded by Remember cues. In the long SOA condition, however, the detection time was statistically equivalent for probes following the two kinds of cues. This result was viewed as evidence that directed forgetting is an active process and demands more efforts than remembering, at least in the initial stage of the processing of Remember/Forget cues. The discrepancy between the two studies (Fawcett and Taylor, 2008; Marks and Dunaney, 2001) could be due to that different aspects of attention allocation were indexed by the tasks they employed, with probe detection reflecting the bias of spatial attention and lexical decision reflecting the processing efficiency of attributes beyond perceptual analysis. It is therefore of theoretical interest to track the time course of attention allocation to non-perceptual attributes following the Remember/Forget cues with Marks and Dunaney’s procedure. To address this issue, we manipulated the presentation duration of Remember/Forget cues to examine how this variable modulates the lexical decision times to targets preceded by Remember and Forget cues. In addition, the ERP deflection of P200 elicited by the targets was used to index the amount of cognitive resources occupied by the TBR and TBF primes. The P200 wave has been linked to phonological processing in visual word recognition (Carreiras et al., 2005; Hsu et al., 2009; Lee et al., 2006; Liu et al., 2003) and its amplitude has been shown to be sensitive to attentional influences (Blanchet et al., 2007; Luck and Hillyard, 1994; Miniussi et al., 2005). If forgetting the primes is more effortful and engages more resource than remembering them, as suggested by Fawcett and Taylor (2008), there should be less resource available for the phonological processing of targets following TBF primes than those following TBR primes. It was expected that the difference in available resource would be reflected by the P200 wave elicited by the targets. Specifically, targets preceded by Forget cues hence with less resource for phonological processing were expected to elicit a smaller P200 wave than those that were preceded by Remember cues, particularly in the short–cue-duration condition when most resource might still be allocated to the primes upon the presence of the targets.

2. Materials and methods

2.1. Participants

A total of 63 undergraduate students (aged between 18 and 24) from National Central University participated in the experiment. All these participants were right-handed native Mandarin Chinese speakers with normal or corrected-to-normal vision. They were paid for their participation in the experiment. Written consent was obtained from all participants. The 63 participants were assigned to two groups with 30 participants in the short-cue-duration group and 33 participants in the long-cue-duration group. The data from six participants in the short–cue-duration group and nine participants in the long-cue-duration group were excluded because they contributed insufficient (≤16) valid ERP trials to at least one critical experimental condition. All the behavioral and ERP analyses were therefore based on 48 participants, with 24 participants in each of the two cue-duration groups.

2.2. Stimuli

The critical stimuli were 180 word quadruplets, each of which consisted of a prime item, a semantically related target item, a semantically unrelated target item, and another unrelated target item. The prime items were Chinese two-character nouns selected from the Academia Sinica Balanced Corpus of Modern Chinese (Huang and Chen, 1998) with the mean frequency of 256 per million. Both the semantically related and unrelated target items were also two-character nouns. The related target items were selected from the free association reactions to the prime items obtained from 20 undergraduate students who did not participate in the current experiment. The unrelated target items were selected from the corpus and were not found in the free association reactions to the prime items. There was no significant difference [t(179) = 0.7, p > .94] between the mean frequencies of the related and unrelated target items (494 and 495 per million, respectively). The nonce words targets were generated by rearranging real two-character words that were not used in the current experiment. None of the nonwords or their homophones was listed in the corpus. The 180 word quadruplets were evenly assigned to one of the following six conditions, in which the prime item was followed by a Remember cue and the semantically related target (hereafter abbreviated to “wR®”), a Remember cue and the semantically unrelated target (“wR®u”), a Remember cue and the nonword target (“wR®n”), a Forget cue and the semantically related target (“wF®”), a Forget cue and the semantically unrelated target (“wF®u”), or a Forget cue and the nonword target (“wF®n”). The allocation of the word quadruplets to the six conditions was counterbalanced across participants. In addition to the critical stimuli, another 60 nonword–real word (“n–w”) pairs and 120 nonword–nonword (“n–n”) pairs were used as primes and targets in the filler trials where no Remember/Forget cues were delivered. The real words and nonwords used in these filler trials were generated in the same way as those of the critical quadruplets and were presented for all participants. There were therefore 360 trials across the experiment. For both the prime and target items, half were real words and the other half were nonwords. The
Remember/Forget cue was delivered in trials whose prime items were real words. The presentation order of the 360 trials was randomly assigned for each participant.

2.3. Procedure

Prior to the experiment, participants were fitted with an elastic electrode cap and then seated at a viewing distance of 80 cm away from a monitor. Participants then engaged in a study phase during which they made lexical decisions to both the primes and the target items. They were instructed to remember or to forget the prime item upon the presentation of the Remember/Forget cue when the prime item was a real word. Participants were also told that nonwords and target items in the lexical decision task would not be included in the subsequent memory test. Each trial started with the presentation of the fixation character “+” for 500 ms on the center of the screen, followed by the presentation of the prime item. The prime item was displayed for 1000 ms during which participants judged whether the item was a real word or a nonword. The prime item was then replaced by a Remember cue (“RRRRR”) or a Forget cue (“FFFFF”) when it was a real word; and was replaced by a neutral cue (“********”) when it was a nonword. The duration of the cue was 500 ms for participants of the short-cue group and 1500 ms for those of the long-cue group. After the cue disappeared, the screen was blank for 250 ms. The target item was then presented for 1000 ms, during which participants made the second lexical decision. Immediately after the target item, a neutral cue (“********”) was shown for 1500 ms followed by a screen of 2500 ms, during which the next trial was begun. Then, the primes and to the targets, were made by pressing one of two response keys with the index finger of each hand. The mapping of the hand to response category (word vs. nonword) was counterbalanced across participants. After the study phase, participants engaged in a backward counting task for approximately 5 min. They were then instructed to recall all of the prime words regardless of whether the words had been followed by a Remember cue or a Forget cue in the lexical decision task. The recall test was conducted by writing down the words on a sheet of paper provided by the experimenter. There was no time limit for the recall test. To ensure that participants followed the Remember/Forget instructions in the study phase, they were told prior to the lexical decision task that there would be a 5-dollar bonus and a 10-dollar penalty respectively for each of the TBR and TBF prime words recalled in the subsequent test, on top of an initial amount of 250 New Taiwan Dollars (NTD). On the other hand, to ensure that participants reported all the prime words they could recall, they were told prior to the test phase that in addition to the 5-dollar bonus for each recalled TBR word, there would be a bonus, rather than penalty, of 10 dollars when a TBF prime word was recalled.

2.4. ERP recording

EEG was continuously recorded during the study phase from 64 silver/silver chloride electrodes, 62 of which are embedded in an elastic cap (Quick-Cap, Neuromedical Supplies, Sterling, TX, USA). 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. A ground electrode was placed on the forehead anterior to the Fz electrode. Vertical and horizontal EOG were recorded bipolarly from electrodes placed above and below the right eye, and on the outer canthus 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 by SYNAMP2 (Neuroscan, El Paso, TX, USA) with a bandpass of 0.05–70 Hz (3 dB points). Inter-electrode impedance was kept below 5 kΩ.

2.5. ERP analysis

Two sets of ERP analyses were separately conducted for the Remember/Forget cues and the target items. The cue-related potentials were computed for epochs of 850 ms in the short-cue condition and 1850 ms in the long-cue condition, both beginning 100 ms prior to the onset of the cues. The epochs for the short and long-cue conditions were of different lengths to ensure that cue-related ERPs in both conditions encompass the 250 ms blank period between the offset of the cues and the onset of the following targets, such that we could assess whether the cue-related ERP differences continued to the pre-target baseline period hence affected the analyses/interpretations of the target-related ERPs. For the target items, ERPs were computed for epochs of 1100 ms beginning 100 ms prior to the onset of the targets in the lexical decision task. 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 epoch data.

1 The actual payment to the participants was based on the latest payoff scheme announced prior to the recall test, i.e., 250 NTD plus 5 NTD for each TBF word recalled and 10 NTD for each TBF word recalled. In the post-experiment debriefing, no participants reported doubts on the validity of the two payment schemes.

### Table 1

| Table 1 Mean proportions (S.D. in parentheses) of correct recall of primes as a function of Remember/Forget cues and the type of the following target. |
|---|---|---|---|
| Remember/Forget cue | Type of the subsequent target | Related | Unrelated | Nonword |
| Remember/Forget cue duration = 500 ms | | | | |
| Remember | .26 (.13) | .20 (.12) | .19 (.12) |
| Forget | .05 (.07) | .02 (.04) | .02 (.04) |
| Remember/Forget cue duration = 1500 ms | | | | |
| Remember | .36 (.19) | .35 (.22) | .39 (.23) |
| Forget | .02 (.02) | .01 (.01) | .01 (.02) |

3. Behavioral results

3.1. Free recall of the prime items

Table 1 displays the recall rates of the prime items as a function of the Remember/Forget cues and the types of the subsequent target items (semantically related, semantically unrelated, and nonword) in the two cue-duration (500 ms and 1500 ms) conditions. The data were analyzed with a mixed-design ANOVA employing the between-subjects factor of cue duration and the within-subjects factors of Remember/Forget cue and subsequent target type. The main effect of cue duration was significant [F(1,46) = 7.02, p = .01], reflecting that more primes were recalled in the long-cue condition than in the short condition. The main effect of Remember/Forget cue was also significant [F(1,46) = 131.15, p < .001], which revealed the directed forgetting effect that TBR primes were better recalled than TBF ones. The interaction between Remember/Forget cue and cue duration was also significant [F(1,46) = 13.9, p = .001], suggesting that the directed forgetting effect on the primes was larger in the long-cue condition than in the short-cue condition. The interaction between Remember/Forget cue and subsequent target type was not significant (F < 1), revealing no evidence that the directed forgetting effect on the prime items was modulated by the type of the subsequent targets. The interaction between subsequent target type and cue duration was significant [F(2,92) = 7.23, p = .001]. Follow-up analyses showed that the recall performance of the primes was modulated by subsequent target type in the short-cue condition [F(2,46) = 17.22, p < .001]. Primes followed by semantically related targets were better recalled than those that were followed by unrelated or nonword targets (p < .001 in both cases). In the long-cue condition, however, the recall rate of the primes was not modulated by the type of the subsequent targets [F(2,46) = 1.46, p = .24].

3.2. Reaction times of lexical decisions to the target items

Prior to this analysis, trials with lexical decision times longer or shorter than two standard deviations from the means of each individual participant were removed. Table 2 lists the reaction times of correct trials in the lexical decisions to the targets as a function of the Remember/Forget cues and target types in the two cue-duration conditions. A mixed-design ANOVA on target items that were real words (i.e., “wRw”, “wRu”, “wFw”, and “w Fu” trials) showed that the main effect of target type (related vs. unrelated) was significant

2 The behavioral responses of lexical decisions to the primes were also recorded. The lexical decision times to the correctly identified real-word and nonword primes were 604 (sd = 40) and 621 (sd = 55) ms in the short-cue condition. The corresponding values were 609 (sd = 44) and 617 (sd = 47) ms in the long-cue condition. It was faster to identify a real word than to reject a nonword [F(1,46) = 6.15, p = .02]. Given that the primes were shown before the Remember/Forget cues and the target items, the lexical decision times to the primes, as expected, were not modulated by cue duration, cue type and target type.
Table 2

<table>
<thead>
<tr>
<th>Remember/Forget cue</th>
<th>Target type</th>
<th>Related</th>
<th>Unrelated</th>
<th>Priming</th>
<th>Nonword</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remember/Forget cue duration = 500 ms</td>
<td>Reminder</td>
<td>637 (59)</td>
<td>670 (51)</td>
<td>33</td>
<td>710 (50)</td>
</tr>
<tr>
<td></td>
<td>Forget</td>
<td>585 (44)</td>
<td>618 (40)</td>
<td>34</td>
<td>690 (52)</td>
</tr>
<tr>
<td>Forget–Remember</td>
<td>-53</td>
<td>-52</td>
<td>1</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>Remember/Forget cue duration = 1500 ms</td>
<td>Reminder</td>
<td>646 (57)</td>
<td>686 (63)</td>
<td>40</td>
<td>712 (54)</td>
</tr>
<tr>
<td></td>
<td>Forget</td>
<td>613 (63)</td>
<td>642 (51)</td>
<td>29</td>
<td>694 (58)</td>
</tr>
<tr>
<td>Forget–Remember</td>
<td>-33</td>
<td>-44</td>
<td>-11</td>
<td>-17</td>
<td></td>
</tr>
</tbody>
</table>

$[F(1,46) = 119.81, p < .001]$, reflecting the semantic priming effect that the lexical decision was faster for semantically related targets than unrelated ones. The main effect of Remember/Forget cue was also significant $[F(1,46) = 126.4, p < .001]$, suggesting that the lexical decision time was longer for targets preceded by a Remember cue than those that were preceded by a Forget cue. The interaction between Remember/Forget cue and target type was not significant ($F < 1$), revealing no evidence that the semantic priming effect was modulated by the Remember/Forget cue. The main effect of cue duration was not significant $[F(1,46) = 1.06, p = .31]$, nor was its interactions with Remember/Forget cue $[F(1,46) = 2.84, p = .10]$ and target type ($F < 1$). The main effect of cue duration was not significant, nor was its interaction with Remember/Forget cue (both $F$s < 1).

4. ERP results

The Greenhouse–Geisser correction for non-sphericity was applied when necessary. $F$ ratios are reported with Greenhouse–Geisser epsilon values ($\varepsilon$) and adjusted $p$-levels.

4.1. Remember/Forget cues

The analyses of the cue-related potentials served two purposes: to replicate previous findings of the ERP differences between Remember and Forget cues (e.g., Hsieh et al., 2009; Paz-Caballero and Menor, 1999; Paz-Caballero et al., 2004), and to assess whether the cue-related ERP differences continued to the pre-target baseline period hence affected the analyses/interpretations of the target-related ERPs. ERPs were separately averaged for the Remember cues and the Forget cues in the two cue-duration conditions, with 24 participants in each condition. The mean trial numbers (range in brackets) for Remember and Forget cues were 83 (71–90) and 84 (68–89) in the short-cue condition. The corresponding numbers in the long-cue condition were 67 (24–86) and 62 (31–83). The grand–average ERPs elicited by the cues are displayed in Fig. 1.

For comparing the processing of Remember and Forget cues, ERPs were quantified by measuring the mean amplitudes of 250–450 and 460–560 ms time periods. These two time periods roughly correspond to the time regions where our previous study found a posterior positivity and an anterior positivity for the Remember and Forget cues respectively (Hsieh et al., 2009). Data from the midline electrodes (Fz, Cz, Pz) and lateral electrodes (F3/4, C3/4, P3/4) were factorized into three levels (anterior, central, and posterior) of (left, midline, and right) of left-right scalp region. In both the short- and long-cue conditions, the ERPs elicited by the Remember cues were more positive-going than those elicited by the Forget cues [short cue: $F(1,23) = 76.07, p < .001$; long cue: $F(1,23) = 64.81, p < .001$]. The interaction between Remember/Forget cues and caudality was significant [short cue: $F(2,46) = 8.79, p = .002$, $\varepsilon = .77$; long cue: $F(2,46) = 6.24, p = .004$, $\varepsilon = .82$], reflecting that the larger positivity for Remember cues in comparison to Forget cues was more pronounced over the central and posterior scalp regions than the anterior region. In the later time period, the interaction between Remember/Forget cues and caudality was also significant [short cue: $F(2,46) = 42.6, p < .001$, $\varepsilon = .75$; long cue: $F(2,46) = 12.3, p = .001$, $\varepsilon = .63$]. Follow-up analyses showed that the Remember cues remained more positive than Forget cues over the posterior sites [short cue: $F(1,23) = 7.99, p = .01$; long cue: $F(1,23) = 11.24, p = .003$]. Nevertheless, over the anterior recording sites, the ERPs elicited by the Forget cues were more positive-going than those elicited by the Remember cues in the short-cue condition [short cue: $F(1,23) = 11.87, p < .001$].

Correlation analyses were conducted to examine whether the cue-related ERPs relate to the behavioral semantic priming effect on the subsequently presented targets. In the short-cue condition only, there was a positive correlation between the amplitude of the ERPs elicited by the Remember cues over the posterior sites and the magnitude of the semantic priming effect ($r = .44, p = .03$ and $r = .42, p = .04$ for the time windows of 250–450 and 460–560 ms]. That is, the larger P3b-like wave elicited by the Remember cue, the greater advantage for lexical decisions to related targets as opposed to unrelated ones. No such correlation was found in the long-cue condition. There was also no significant correlation between the ERPs elicited by the Forget cues and the semantic priming effect, either in the short or in the long-cue condition.

The contrasts between Remember and Forget cues were also conducted on the blank period between the offset of the cues and the onset of the target items (i.e., 500–750 ms in the short-cue condition and 1500–1750 ms in the long-cue condition). The interaction between Remember/Forget cues and caudality was significant in both cue-duration conditions [short cue: $F(2,46) = 11.97, p < .001$, $\varepsilon = .67$; long cue: $F(2,46) = 9.78, p = .001$, $\varepsilon = .84$]. Follow-up analyses revealed a positivity associated with Forget cues in comparison to Remember cues over the posterior sites in the short-cue condition $[F(1,23) = 16, p < .001]$. There were, however, no differences between these two types of cues over the anterior and central sites [all $F$s < 1]. There were also no differences between Remember and Forget cues on the electrode sites of F3/4, F5/6, and F7/8, which were included in the F200 analyses of target items (all $F$s < 1).

4.2. Target items

ERPs elicited by the target items of the “wRr”, “wRu”, “wFr”, and “wFu” trials were separately averaged for the two cue-duration conditions. Only trials with correct lexical decision judgments were included in the average. Trials whose lexical decision times to the targets were longer or shorter than two standard deviations from the means of each individual participant were also rejected. The mean trial numbers (range in brackets) for these four types of trials were 26 (17–30), 24 (16–29), 26 (19–30), 24 (16–30) in the long-cue condition and 25 (19–30), 23 (16–28), 26 (16–30), 23 (16–30) in the short-cue condition.

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1 There were fewer valid ERP trials in the long-cue condition than in the short-cue condition because epochs in the former condition were 1000-ms longer and more likely to contain artifacts than those in the latter condition. One concern is that the difference between the trial numbers in the two conditions might bias the results. Nevertheless, the trials numbers were reasonably sufficient and the enhancement of signal/noise ratios (estimated by the square root of trial numbers) was close in the two cue duration conditions. In addition, following S. Luck’s argument (Luck, 2005), the dependent variable used here (mean amplitude) is an unbiased measure. Based on these reasons, it is reasonable to presume that the different trial numbers in the short- and long-cue conditions would not cause serious problems in the results.

4 We thank an anonymous reviewer for raising this point.
ERPs Elicited by the Remember/Forget Cues

Fig. 1. Grand-average ERPs elicited by the Remember/Forget cues in the short (upper panel) and long-cue condition. Note that the time scales for the two cue conditions were different. The rectangles on the panels mark the two time windows (250–450 and 460–560 ms) during which significant differences were found for the ERPs elicited by the two types of cues.

4.2.1. P200

The analysis of P200 was based on the mean amplitude of the 180–230 ms time period. Data from the anterior lateral recording sites (F3/4, F5/6, F7/8; see Fig. 2 for waveforms recorded at F5 and F6) were factorized into two levels (left vs. right) of hemisphere. The main effect of Remember/Forget cue was marginally significant \( F(1,46)=4.27, p=.05 \). The interaction between cue-duration and Remember/Forget cue was significant \( F(1,46)=13.42, p<.001 \). Follow-up analysis in the short-cue condition showed that the effect of Remember/Forget cue was significant \( F(1,23)=11.53, p<.002 \), reflecting a larger P200 for targets preceded by a Remember cue than those that were preceded by a Forget cue. In the long-cue condition, there were no significant effects involving the factors of Remember/Forget cue or target type.

4.2.2. N400

The analysis of N400 was based on the mean amplitudes of the 300–550 ms time period from midline electrodes (Fz, Cz, Pz) and lateral electrodes (F3/4, C3/4, P3/4; see Figs. 3 and 4 for the grand-average waveforms). These electrodes were factorized into three levels (anterior, central, and posterior) of caudality and three levels (left, midline, and right) of left-right scalp region. The results showed that the main effect target type was significant \( F(1,46)=82.19, p<.001 \), reflecting that the waveforms were in general more negative for unrelated targets than related ones. The interaction between target type and caudality was significant \( F(2,92)=12.16, p<.001, \varepsilon=.79 \), so was the interaction between target type and left-right scalp region \( F(2,92)=12.12, p<.001, \varepsilon=.88 \). These results suggested that the negativity associated with unrelated targets in comparison to related ones was more pronounced at the central/posterior sites than anterior sites and over the midline/right scalp region than the left region. The interaction between Remember/Forget cue and target type was not significant \( F(1,46)=2.84, p=.10 \). However, the interaction between cue duration, Remember/Forget cue, target type, and caudality was significant \( F(2,92)=4.33, p=.03, \varepsilon=.7 \). This four-way interaction suggested that the modulation of Remember/Forget cue on the negativity associated with unrelated targets, as can be seen in Fig. 5A and D, was pronounced at posterior sites in the short-cue (500 ms) condition but at anterior sites in the long-cue (1500 ms) condition. Follow-up analyses in the two cue conditions showed that the three-way interaction between Remember/Forget cue, target type, and caudality was significant \( F(2,46)=4.02, p=.04, \varepsilon=.61 \) in the short-cue condition but not in the long-cue condition.

A topographical analysis was conducted to compare the scalp distributions of the N400 effect elicited by the target items preceded by Remember cues and those that were preceded by Forget cues (Fig. 5B and D). Prior to the topographical analysis, the difference data from the 62 recording sites, obtained by subtracting the mean amplitudes of unrelated targets from those of related ones, were range-normalized with the max–min method to avoid the confounding between any differences in the magnitudes of the 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 analysis. The results showed that the interaction between Remember/Forget cue and recording site was significant in the short (500 ms) cue condition \( F(61,1403)=3.77, p=.002, \varepsilon=.09 \) but not in the long (1500 ms) cue condition \( F<1 \). These findings indicated that the
Fig. 2. The ERP waveforms elicited by target items at F5 and F6 electrode sites, overlaid by the Remember/Forget cue types on the preceding primes, in the short (left panel) and long (right panel) cue conditions.

Fig. 3. Grand-average ERPs elicited by related and unrelated target words that were preceded by Forget cues (left) and Remember cues (right) in the long (1500 ms) cue condition.

The distribution of the N400 effect elicited by unrelated target items preceded by a Remember cue was different from that preceded by a Forget cue when the Remember/Forget cues were shown for a short time period (Fig. 5B) but not when the cue was shown for a long duration (Fig. 5D).

5. Discussion

The behavioral data gave rise to a reliable directed forgetting effect. Prime items that were followed by Remember cues in the lexical decision task were subsequently better recalled than those
that were followed by Forget cues. When the presentation duration of the Remember/Forget cues decreased from 1500 ms to 500 ms, the directed forgetting effect was reduced but far from being abolished. The reliable directed forgetting effects indicated that participants in both cue-duration conditions complied with the Remember/Forget instructions embedded in the lexical decision task. In the lexical decision to the target items, a robust semantic priming effect was revealed. Target words preceded by semantically related primes elicited a faster response than those that were preceded by unrelated primes. The semantic priming effect was however not modulated by the Remember/Forget instructions on the primes. In addition, the lexical decision time was longer for targets preceded by Remember cues than those that were preceded by Forget cues, irrespective of the prime–target relationship. All these lexical decision results to the target items were not modified by the presentation duration of the Remember/Forget cues.

The behavioral results therefore replicated the findings of Marks and Dulaney (2001). The monetary incentives, delivered by the instructions of penalty at study and bonus at test for recalling TBF items, did not change the patterns of semantic priming effects for the targets and the directed forgetting effects for the primes reported by Marks and Dulaney. The current finding of a low recall rate for TBF primes when bonus was offered at test replicated previous studies (e.g., Basden et al., 1994; Macleod, 1999; Woodward and Bjork, 1971) that participants were not withholding TBF items, and that demand characteristics did not play a role in directed forgetting. On the other hand, although previous studies have found that memory performance could be enhanced by monetary incentives delivered during the study phase (e.g., Adcock et al., 2006; Shigemune et al., 2010), it has been shown that the enhancement was based on the increase of dopamine release in the hippocampus regions during memory consolidation and only revealed in a delayed test but not in immediate test (Bunzeck et al., 2010; Murayama and Kuhbandner, 2011). This might explain why the monetary incentive delivered at study did not change the patterns of semantic priming and directed forgetting effects reported by Marks and Dulaney (2001), because the lexical decision task was conducted immediately after the presence of the Remember/Forget cues and the recall test was not conducted soon after the study phase.

The analyses of the ERPs elicited by the target items, however, showed findings different from the behavioral results. A reliable N400 semantic priming effect was revealed in the lexical decision task. Targets preceded by semantically unrelated primes elicited a greater N400 wave than those that were preceded by related primes. The N400 effect was observed whether the prime items were TBR or TBF and whether the Remember/Forget cues were long or short. Nevertheless, as can be seen from Fig. 5, the N400 effect tended to be greater for targets preceded by Remember cues than those that were preceded by Forget cues. A significant interaction suggested that the modulation of Remember/Forget cues on the N400 effect was most pronounced over anterior/central scalp regions in the long-cue condition but over posterior scalp regions in the short-cue condition (Fig. 5A and C). These findings, in contrast to the behavioral results, indicated that the semantic processing that took place following the presence of the Remember/Forget cues might not be entirely equivalent for TBR and TBF primes. Importantly, in the short-cue condition only, the scalp distribution of the N400 effect was different for targets preceded by Remember cues and those that were preceded by Forget cues (Fig. 5B). The different scalp distributions, reflecting non-equivalent neural substrates underlying the two sets of N400 effects, implicated qualitative rather than quantitative differences between the semantic processing of TBR items and that of TBF items in the short-cue condition. In the long-cue condition, on the other hand, the scalp distributions of the N400 effects were indistinguishable for targets preceded by Remember cues and those that were preceded by Forget cues. Importantly, we also found that in the short-cue condition only, the amplitude of a P3b-like wave elicited by the Remember cues positively correlated with the magnitude of the behavioral semantic priming effect on the subsequently presented target items. The P3b-like wave elicited by the Remember cues has been reported.
to be correlated with directed forgetting effect on a recognition test (Hauswald et al., 2011) and has been thought to reflect the amount of resource allocated to the processing of the TBR items in our previous study (Hsieh et al., 2009). The data therefore suggested that the different modulations of the Rememer and Forget cues on the semantic processing maintained only for a limited temporal interval. One caveat in the interpretation of the topographic data is that different scalp distributions need not serve as direct evidence that TBR items were processed more elaboratively than TBF items. The differences in topographies have been used to examine whether the neural mechanisms underlying different cognitive operations are distinguishable (e.g., Antal et al., 2000; Kiefer, 2001, 2005; Kounios and Holcomb, 1994; Nittono et al., 2002). Nevertheless, ERP or MEG studies employing dipole fitting or other source localization methods are needed to provide precise location information of the neural mechanisms underlying the two sets of N400 effects, based on which the argument that Rememer and Forget cues result in different depths of processing on the TBR and TBF items could be further verified.

In addition to the N400 effect, the P200 waves of the targets were also examined to investigate whether intentional forgetting demands more efforts than remembering. We found that the P200 elicited by the targets was not modulated by the prime-target relationship, revealing no evidence that the semantic processing of the primes was reflected by this deflection. However, the Rememer/Forget cues in the short-cue condition were found to modulate the magnitude of P200. Targets preceded by Forget cues yielded a smaller P200 in comparison to those that were preceded by Rememer cues. Based on the following reasons, we consider this finding as supportive evidence that it demands more cognitive resource to intentionally forget an item than to remember it. Previous studies have shown that visually presented words elicited a larger P200 when greater attentional resource was allocated to the orthographic and phonological processing of these words (Bentin et al., 1999; Carreiras et al., 2005; Hsu et al., 2009; Liu et al., 2003). If to intentionally forget an item indeed demands more efforts than to remember it, a greater amount of cognitive resource would be engaged when a prime item received an instruction of Forget, as opposed to when the instruction was to remember it. It follows that, subsequent to the presentations of the Rememer and Forget cues, a lesser amount of resource would be available for targets preceded by Forget cues, as compared with those that were preceded by Rememer cues. The P200 waves elicited by the targets should therefore be smaller when the preceding prime item was TBF, as opposed to when the prime was TBR. The way that Rememer/Forget cues modulated the P200 wave observed here is consistent with this prediction and lends support to the view that intentionally forgetting is more effortful than remembering.

In the long-cue condition, on the other hand, the Rememer/Forget cues gave rise to no effects on the P200 elicited by the target items. It indicated that only in the early stage following the presence of the Rememer/Forget cues did these cues modulate the attentional resource allocation to the target items. In the later stage, the allocation of attentional resource was of no difference whether the targets were preceded by Rememer cues or by Forget cues. As a result, parallel to their effects on the semantic processing of the primes, the Rememer/Forget cues’ modulation on the attentional resource allocation was only sustained for a limited temporal interval. Why was there the temporal limitation of Rememer/Forget cue’s modulation on the resource allocation to the targets? One possibility is that the amount of resource consumed by the prime items, thus the spared resource that could be allocated to the target items, in the early stage was different from that in the late stage subsequent to the presence of the Rememer/Forget cues. In the early stage, a great amount of resource might have been devoted to the prime items. The deployment of the spared resource, which was relatively scarce, to the target items was therefore greatly modulated by the Rememer/Forget cues. In the later stage, by contrast, the primes might have been processed to a level that the initially occupied resource could be released. The deployment of the spared resource, which was plentiful when compared with that in the early stage, to the target items was hence immune to the modulation of the Rememer/Forget cues. We consider this interpretation to be conceptually analogous to the load theory of selective attention (Lavie, 1995), which argues that the allocation of resource to goal-irrelevant stimuli is modulated by the extent to which the resource has been consumed by goal-relevant stimuli. In a similar vein, the resource allocation to the target items in the current experiment might have been modulated by the extent to which the resource was consumed by the prime items.

The discussion above hinges on the assumption that the P200 wave was smaller for targets preceded by Forget cues because the processing of Forget cues demands more attentional resources than Rememer cues. It is therefore important to elucidate other interpretations that might account for the ERP differences between targets preceded by the two types of cues. First, the Rememer and Forget cues could have elicited ERPs whose differences sustained to the onset of the targets, hence resulted in the target-related P200 differences. Furthermore, considering the temporal distance between cue and target onsets, the cue-related ERP differences prior to target onsets might be larger in the short-cue condition than in the long-cue condition, such that the target-related P200 was modulated by the cues in the former but not in the later condition. Indeed, as a replication of prior studies (Hsieh et al., 2009; Paz-Caballero et al., 2004), we found a posteriorly distributed positivity for Rememer cues and an anteriorly distributed positivity for Forget cues. However, when examining the 250 ms blank period between the offset of the cues and the onset of the targets, the ERPs elicited by the two types of cues did not differ from each other over the anterior sites where the target-related P200 analyses were conducted. Although the cue-related ERP differences over the posterior sites continued to target onsets, these sites were not where the P200 waves were analyzed. There was therefore no evidence suggesting that the smaller P200 for target preceded by Forget cues than those that were preceded by Rememer cues was caused by a sustained cue-related ERP differences in the short-cue condition. We also consider the cue differences over the posterior sites irrelevant to the finding that the target-related N400 effects were indistinguishable in the long-cue condition but of different topographies for the two types of cues in the short-cue condition. This is because the topographic analysis were based on the difference waves between related and unrelated targets that have been range-normalized with the max–min method, which should have removed the possible influences of Rememer/Forget cue differences on the pre-target baseline period (Wilding, 2006).

It should be noted that although we view the modulation of Rememer/Forget cues on target-related P200 waves as reflecting more attentional resources were allocated to the Forget cues than to the Rememer cues, we do not argue that the item-method directed forgetting effect exclusively results from the inhibition on the TBF items. As revealed in the recall performance, the larger directed forgetting effect in the long-cue condition than in the short-cue condition comes from more TBR items being recalled in the former than in the latter condition. In addition, more semantically related targets intruded in the recall when the primes were TBR. Both findings support that TBR items engaged more elaborative or richer rehearsals than TBF items. What we have argued and demonstrated here is that the directed forgetting effect also receives contributions from the inhibition of TBF items even when the payoff schemes of rewarding the recall of TBR items have encouraged the strategies of selective rehearsal. The temporal limitation of Rememer/Forget cues’ modulation on the attention allocation to the target items, on
the other hand, the inhibition of the TFB items might only need to sustain for a short while. This could also explain the indistinguishably recall rates of TFB items in the short and long-cue conditions. The low TFB recall rates in both cue-duration conditions might not simply reflect a floor effect. Instead, it could indicate that a short interval of inhibition is sufficient to block further processing of the TFB items held in short-term memory. The resource could then be released for other cognitive operations, such as rehearsing previously presented TBR items.

6. Conclusion

To sum up, the current study has three main ERP findings. First, by employing the N400 effect as an index of semantic processing, we showed that the TBR and TFB items in the item-method directed forgetting receive different kinds of semantic processing. Second, by exploiting the characteristics of the P200 wave that its amplitude is sensitive to attentional influences, we demonstrated that forgetting an item is more effortful than remembering it. Finally, by manipulating the duration of the Remember/Forget cues, we found that there is a temporal limitation for the Remember/Forget cues’ modulations on semantic processing and attentional resource. As suggested by Fawcett and Taylor (2008), these findings contradict with the argument that TFB items in item-method directed forgetting are passively decayed following the presence of the Forget cues. Rather, these data lend support to the view that forgetting is an active process and might demand more resource than remembering. The current study further revealed that the attentional resource engaged by intentional forgetting is not confined to spatial attention but also includes resources for phonological processing. Further studies are needed to investigate the mechanisms underlying the temporal limitation of Remember/Forget cues’ effects on semantic processing and attentional resource allocation.

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References


