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Decreased inhibitory control of negative information in directed forgetting

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ABSTRACT

A great deal of evidence suggests that emotion enhances memory. Thus, it is possible that emotional information may be harder to forget. Here, we investigated this issue in the item-method directed forgetting paradigm using event-related fMRI. Behavioral results showed that although the directed forgetting effect was significant for both negative and neutral words, it was significantly reduced for negative words. At the neural level, the initial viewing of negative words was associated with larger activations in inferior frontal gyrus and superior parietal lobule when contrasted with neutral words, which reflected the capture of attention by negative content. Directed forgetting instructions for both negative and neutral words elicited stronger activations in frontal and parietal cortex, consistent with the engagement of an active inhibitory process. Surprisingly, whereas successful directed forgetting of neutral words elicited stronger activations in right middle frontal gyrus compared with incidental forgetting, no such activation was observed for negative words. The lack of activation for negative words may be due to an attentional bias in processing negative words, which may briefly interfere with the deployment of inhibitory control. The present findings are consistent with the engagement of an active forgetting mechanism that contributes to the item-method directed forgetting. However, evidence of impeded inhibitory control suggests that forgetting negative words is harder.

1. Introduction

Previous research has suggested that emotion can enhance memory (Phelps and Sharot, 2008). Importantly, the benefits for emotional information have been documented with a range of stimuli, such as words and pictures (Brandt et al., 2013; Nowicka et al., 2010; Yang et al., 2012). From an evolutionary perspective, this may be beneficial. Enhancement of emotion may increase survival by facilitating rapid and accurate responding to familiar stimuli, which can elicit prominent emotional reactions. However, the persistence of memories for negative experiences or unpleasant events can also wreak havoc on people's lives (Butler and James, 2010). One way in which people cope with unwanted memories is by intentionally forgetting them. Intentional forgetting engages memory mechanisms that can prevent irrelevant or outdated information from interfering with memory (Anderson and Hanslmayr, 2014; Bjork, 1989). However, if emotion enhances memory (Doerksen and Shimamura, 2001; Fox et al., 2001), emotional information may be harder to forget.

One experimental method used to investigate intentional forgetting is the directed forgetting paradigm. Two variants of the directed forgetting paradigm exist: the item-method and the list-method (Basden and Basden, 1998; Bjork, 1989; Macleod, 1999). In the item-method directed forgetting procedure, the study items are individually cued as to-be-remembered (TBR) or to-be-forgotten (TBF) on a trial-by-trial basis. In the list-method, the study items are divided into two lists. Following the first list, half of the participants are asked to forget these items and the other half to remember these items. Then, the participants study the second list, which is followed by a surprise final test for the original list. In both paradigms, a directed forgetting effect arises when items cued to be forgotten show worse memory compared with items cued to be remembered.

The mechanisms underlying the item-method and list-method paradigm are often thought to be different. In the item-method, theoretical accounts have focused on selective rehearsal and attentional inhibition (Basden, 1996; Macleod, 1999; Wylie et al., 2008). According to the selective rehearsal hypothesis, each item is maintained in working memory until the memory cue is presented. A cue to remember is proposed to lead participants to elaborately encode the item, whereas a cue to forget leads participants to drop the item from working memory and not to elaborately encode it. In contrast, the attentional inhibition

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hypothesis emphasizes that a cue to forget is accompanied by active, inhibition-related processing that interrupts further processing of the item and blocks the encoding of the item into long-term memory. In the list-method, the retrieval inhibition mechanism is proposed to account for the directed forgetting effect (Basden et al., 1993; Bjork, 1989). Because the item in the list-method has been encoded into long-term memory when a cue to forget is received, its existing representation cannot be readily expunged. Instead, the TBF cue causes the representation of that item to be inhibited such that on later retrieval tests, its reactivation is less probable than the reactivation of other items that have not been inhibited (Anderson, 2005; Anderson and Hanslmayr, 2014). Importantly, given that the selective rehearsal and attentional inhibition are posited to work together to support item-method directed forgetting, the item-method allows for the study of not only encoding but also inhibition. Additionally, because only a subset of items are successfully remembered or forgotten, the item-method also enables us to study the intentional forgetting (i.e., TBF trials that are successful and lead to forgetting) and incidental forgetting (i.e., TBR trials that are unsuccessful and lead to forgetting). Considering these advantages of the item-method, the present study was concerned exclusively with the item-method paradigm.

The brain correlates of item-method directed forgetting have been explored in a rapidly increasing number of studies. Evidence from event-related potentials (ERPs) shows that TBF cues elicit enhanced prefrontal positivities relative to TBR cues, which is considered to support the attentional inhibition account (Brandt et al., 2013; Paz-Caballero et al., 2004; Yang et al., 2012). Additionally, fMRI studies using the item-method directed forgetting show that TBF cues, relative to TBR cues, elicit activations mainly in lateral prefrontal and parietal cortices, which also is consistent with the possibility of an active inhibitory process acting on TBF items (Rizio and Dennis, 2013; Wylie et al., 2008).

The question of whether emotional information is harder to forget is one that has recently begun to be addressed. Moreover, this question has primarily been demonstrated by researchers who have sought to determine whether emotional information is harder to forget in clinical populations (Cloitre et al., 1996; Dumont, 2000; Elzinga et al., 2000; Korfine and Hooley, 2000; Mcnally et al., 1999). Unfortunately, however, behavioral research in healthy individuals has reported inconsistent findings (Brandt et al., 2013; Hauswald et al., 2011; Yang et al., 2012). Some studies suggest that negative memories show less directed forgetting than do neutral memories, whereas others indicate that negative and neutral memories are comparably forgettable. For example, Hauswald et al. (2011) found that emotional information was resistant to forgetting, whereas Yang et al. (2012) showed that, compared with neutral information, emotional information exhibited a normal directed forgetting effect.

Additionally, the potential for the directed forgetting mechanism to disrupt emotional memories has been examined using ERP and fMRI. Using the item-method directed forgetting paradigm, Hauswald et al. (2011), Yang et al. (2012) and Brandt et al. (2013) consistently found that TBF cues were associated with a larger frontal positivity relative to TBR cues, suggesting the engagement of an active forgetting process that may inhibit TBF items. However, inconsistencies exist among these ERP studies. Whereas Hauswald et al. (2011) and Brandt et al. (2013) found that the frontal positivities elicited in response to TBF cues were not measurably affected by the potentially disruptive effect of emotional valence, Yang et al. (2012) showed that TBF cues following emotional information elicited enhanced frontal positivities compared with those elicited by neutral information, raising the possibility that more cognitive resources were required to block the encoding of negative information.

To the best of our knowledge, there is only one fMRI study which has investigated the issue of emotional information forgetting using the item-method directed forgetting paradigm. In that study, Nowicka et al. (2010) demonstrated that the intention to forget (measured by comparing activations in response to the TBF cues compared to the TBR cues) negative information led to widespread activations in prefrontal cortex, parietal cortex and occipital cortex, whereas the intention to forget neutral information only resulted in activations in lingual gyrus. In addition, successful directed forgetting (measured by comparing TBF items that were forgotten to TBR items that were forgotten) also was associated with greater activations for negative than for neutral information. These findings suggest that intentionally forgetting emotional information, while possible, may demand more effort than forgetting neutral information, at least in the context of item-method directed forgetting.

An interesting topic within directed forgetting research concerns the neural circuits supporting intentional and incidental forgetting. Intentional forgetting reflects the outcome of participants' conscious action, and is observed on TBF trials in which the item is successfully forgotten (Nowicka et al., 2010; Rizio and Dennis, 2013; Wylie et al., 2008). In contrast, incidental forgetting is a failure of memory encoding arising passively, and is measured on TBR trials in which the item is not successfully remembered (Nowicka et al., 2010; Rizio and Dennis, 2013; Wylie et al., 2008). Wylie et al. (2008) and Rizio and Dennis (2013) reported evidence indicating that intentional forgetting depends on neural processes distinct from those associated with incidental forgetting for neutral information. Specifically, compared with incidental forgetting, intentional forgetting was associated with significant activations in right prefrontal cortex and right superior parietal lobe, which have been theorized to contribute to inhibitory processing; incidental forgetting, by contrast, was associated with encoding-related activities in left inferior frontal gyrus and early visual cortex. Critically, however, existing studies have not fully dissociated the neural processes involved in intentional and incidental forgetting for emotional information. If intentional forgetting of emotional information arises from processes similar to those involved in intentional forgetting of neutral information, intentional forgetting should also be associated with right prefrontal regions thought to be involved in inhibition, whereas incidental forgetting should be associated with the engagement of left inferior frontal regions associated with encoding.

In the current study, we examined the neural mechanisms underlying directed forgetting of emotionally negative and neutral information using the item-method directed forgetting procedure. At the behavioral level, we expected to replicate the overall directed forgetting effect, with TBR items remembered significantly better than TBF items. Moreover, if emotional items yielded stronger encoding and better retention than do neutral items, we further predicted that emotionally negative items might prove harder to forget than would neutral items, yielding a significantly smaller directed forgetting effect for negative items. Neurally, we predicted that, like previous studies, the intention to forget would elicit significantly greater activations in right frontal and parietal cortices, consistent with the possibility that inhibitory control is engaged to terminate encoding. If so, TBF cues should elicit greater activations in these regions compared with TBR cues. Moreover, we predicted that intentional forgetting and incidental forgetting would be mediated by distinct neural processes, with intentional forgetting associated with right prefrontal regions supporting inhibition and incidental forgetting associated with left inferior frontal regions supporting encoding.

Critically, if the encoding of emotional information is harder to inhibit than the encoding of neutral information, one of two patterns should emerge. First, if directed forgetting is similarly successful for both negative and neutral items (as measured by the relative size of the directed forgetting effect for each valence), significantly greater engagement of right frontal cortices should be observed for negative, compared with neutral items. The greater engagement would reflect the increased demand for inhibitory control brought about by the need to inhibit memories with negative valence (Nowicka et al., 2010). Alternatively, if participants are less able to forget negative items (i.e., they show a significantly reduced directed forgetting effect), this may reflect the disrupted engagement of inhibitory processing brought about by attention to negatively valenced content (Hauswald et al., 2011). If so, significantly less engagement of right prefrontal cortex should be observed for negative, compared with neutral information.

2. Methods

2.1. Participants

Twenty-one right-handed, healthy undergraduate students of Southwest University between the ages of 18–25 years (mean age: 22.19 years; 13 females) participated in the experiment for monetary compensation. All participants were Chinese native speakers with normal or corrected to normal vision, and reported no current or past neurological or psychiatric disease. Each participant provided written informed consent to participate in the study, which was approved by the Academic Committee of the School of Psychology, Southwest University in China.

2.2. Procedures

One hundred and twenty eight nouns, which included 64 neutral nouns (Neutral) and 64 negative nouns (Negative), were chosen from the native Chinese Affective Word System (CAWS) (Wang et al., 2008). The two classes of material differed in terms of valence ($F(1130) = 1521.95$, $P < 0.001$) and arousal ($F(1130) = 21.64$, $P < 0.001$), but were matched in terms of frequency ($F(1130) = 0.06$, $P = 0.810$) and familiarity ($F(1130) = 0.76$, $P = 0.388$). These materials were divided into two sets, with each set containing 32 negative and 32 neutral words. One of the sets served as the study items, whereas the other served as the distractions in the recognition task. The words in the two sets did not differ in terms of valence, arousal, frequency and familiarity. To avoid primacy and recency effects (Capitani et al., 1992), we inserted two neutral nouns both at the beginning and end of the study phase. These four neutral nouns were excluded from data analyses.

The experiment employed a traditional item-method directed forgetting paradigm and included two parts: the study and test phases. Scanning occurred only during the study phase. In the study phase, 36 neutral and 32 negative words were presented to each participant. Each word was displayed for 1500 ms, followed by a 1000 ms presentation with a fixation cross and then the memory instruction (a Chinese character "记" for TBR instruction; a "忘" for TBF instruction) was displayed for 2000 ms. Each trial ended with a fixation cross for 1000 ms, 1500 ms, 2000 ms, 2500 ms, or 3000 ms. This postcue length varied pseudo-randomly from trial to trial, with equal probability of each trial. Half of the neutral and half of the negative words were followed by TBR cues, whereas the remaining items were followed by TBF cues. The order of the experimental trials was pseudo-random with the restriction that no more than three consecutive trials with the same type of instruction and valence occurred in sequence.

In the test phase, all 64 nouns from the study phase and the remaining 64 new distractor nouns were presented in a pseudo-random sequence, with the constraint of no more than three consecutive trials with the same type of stimulus (old or new). Each word appeared individually on the screen for 2500 ms, and participants had to perform an old-new recognition test, irrespective of the previous TBR or TBF instructions. Furthermore, participants were asked to respond as quickly and accurately as possible.

2.3. Imaging

Imaging was performed using a Siemens 3 T scanner (Siemens Magnetom Trio TIM, Erlangen, Germany) equipped with an eight-channel phased array coil. Head movement was minimized by restraining the participant's head using a vacuum cushion. Participants viewed visual stimuli on a back-projection screen using an angled mirror mounted on the head coil.

Functional images were acquired using a T2-weighted gradient echo planar imaging (EPI) sequence (axial slices = 25, FOV = 192×192 mm^2, voxel sizes = $3 \times 3 \times 3$ mm^3, thickness/gap = 5/0.5 mm, matrix size = 64×64, TR/TE = 1500/29 ms, flip angle = 90°, 301 volumes). T1-weighted high-resolution anatomical images were also collected for each participant (TR/TE = 1900/2.52 ms, FOV = 256×256 mm^2, matrix size = 256×256, voxel size = $1 \times 1 \times 1$ mm^3, thickness/gap = 1/0.5 mm).

2.4. Behavioral analysis

Statistical analyses were conducted in SPSS 16.0. An alpha level of 0.05 was used for all the analyses. Following Nowicka et al. (2010), the effectiveness of the directed forgetting paradigm was examined by measuring the percentage of studied items correctly recognized in each condition. Thus, recognition rates for TBR and TBF stimuli were analyzed using repeated-measures ANOVAs with type of instruction (TBR/TBF) and valence (Negative/Neutral). In addition, the efficiency of directed forgetting, indexed by the TBR–TBF difference measure, was compared between neutral words and negative words using a paired-samples t-test.

2.5. fMRI data analysis

Image preprocessing was performed using SPM8 (http://www.fil.ion.ucl.ac.uk/spm/; Wellcome Department of Imaging Neuroscience, London, United Kingdom). First, functional images were corrected for differences in slice acquisition timing and for head motion. Second, the structural images for each participant were co-registered to the mean functional images. Third, the unified normalization routine was conducted with voxel size $3 \times 3 \times 5$ mm^3. Finally, the normalized data were smoothed with a Gaussian kernel 8 mm at full-width half-maximum.

Statistical analyses were carried out in the context of the general linear model, in which each event was convolved with the canonical hemodynamic response function. Each event was modeled to the onset of each word or the TBR/TBF instruction. In addition, six realignment parameters for each participant were also included in the model as covariates. We conducted three studies in this research, and the related input parameters were shown as below.

For study words, a design matrix was defined by modeling trials of negative words and neutral words in separate columns. Moreover, each event was modeled to the onset of each word, and each trial was modeled as a separate event (duration = 0). Then, the contrast images from the individual participants were analyzed using a paired-samples t-test to assess the brain activations associated with negative or neutral words.

For our key manipulations of directed forgetting, a 2 (valence: Negative/Neutral) × 2 (memory instruction: TBR/TBF) factorial design generated four conditions for each participant: Negative_TBR, Neutral_TBR, Negative_TBF, Neutral_TBF. These four conditions were all modeled at the onset of the TBR or TBF instruction, and each trial was modeled as a separate event (duration = 0). Then these four conditions from the individual participants were analyzed with a full factorial analysis to assess the neural substrates of directed forgetting for emotionally negative and neutral words. Additionally, we also studied the differences in directed forgetting as a function of valence by comparing negative and neutral words on our key directed forgetting contrasts, namely, we carried out a paired-samples t-test between neutral and negative TBF > TBR contrasts.

Additionally, given that our goal was to examine the neural correlates associated with the directed forgetting of emotional and neutral memories, we also modeled additional conditions based on the combination of memory instruction (TBR/TBF) and the later memory outcome (Remembered/Forgotten) for negative and neutral words separately. In particular, we defined four new conditions in which we focused on the

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subsequently forgotten items from each of our main conditions: TBF_Forget_Negative, TBR_Forget_Negative, TBF_Forget_Neutral, TBR_Forget_Neutral. These four conditions were all modeled at the onset of TBR or TBF instruction, and each trial was modeled as a separate event (duration = 0). Based on these four conditions, we examined the dissociation between intentional forgetting and incidental forgetting by comparing activities associated with the two conditions—TBF_Forget and TBR_Forget—for negative and neutral words separately.

To obtain results which were corrected for multiple comparisons, we used the AlphaSim program to define individual voxel and cluster extent threshold (Yan and Zang, 2010). In this study, an individual voxel threshold of $P < 0.005$ was used in combination with a cluster extent threshold of 46 contiguous voxels, which yielded a corrected threshold of $P < 0.05$. In addition, considering that the small bin sizes of some conditions (i.e., TBR_Forget) may conceal the effective signal and reduce the signal-to-noise ratio,[1] we performed an additional experiment to examine whether our results are reliable or not (for details, see Supplementary materials, Tables S1 and S2).

3. Results

3.1. Behavioral results

Repeated-measures ANOVAs were performed over the hit rates for TBR and TBF stimuli, with type of instruction (TBR/TBF) and valence (Negative/Neutral) as factors (Table 1). The main effect of instruction was significant ($F(1,20) = 76.29$, $P < 0.001$), reflecting the hit rate of TBR words was significantly greater than that of TBF words. Moreover, the main effect of valence ($F(1,20) = 12.54$, $P < 0.01$) showed the hit rate of negative words was greater than that of neutral words. In addition, a significant interaction ($F(1,20) = 8.98$, $P < 0.01$) between instruction and valence was found. A simple effect test indicated that the directed forgetting effect was significant for both neutral and negative words (Neutral words: $F(1,20) = 76.63$, $P < 0.001$; Negative words: $F(1,20) = 40.16$, $P < 0.001$). However, neutral words showed greater directed forgetting effect compared with negative words as revealed by a paired-samples t-test ($t(20) = 3.00$, $P < 0.01$). Moreover, these results were replicated in the second experiment (see Supplementary materials for details, Table S1).

3.2. fMRI results

3.2.1. Activations observed during words viewing

During words viewing, we observed greater activations for negative than for neutral words in bilateral inferior frontal gyrus, right middle temporal gyrus and right superior parietal lobule, whereas there were no any regions showing significantly greater activation for neutral than for negative words (Fig. 1, Table 2). Furthermore, these results were verified by the second experiment (for details, see supplementary materials).

3.2.2. Directed forgetting activations for negative and neutral words

Here, we examined activations associated with the intention to forget, irrespective of whether the intention was successfully implemented (via the contrast, TBF > TBR). For neutral words, this contrast revealed the predicted activations in a right lateralized network that included, critically, right middle and superior frontal gyri. In addition, activations were observed in right middle temporal gyrus, precuneus and inferior parietal lobule (Fig. 2, Table 3). A similar pattern was observed for negative words in the same TBF > TBR contrast. These activations included the predicted right middle frontal gyrus, together with the same network of regions as observed for neutral words, except for a lack of activation in right superior frontal gyrus (Fig. 2, Table 3). Critically, although the intention to forget negative and neutral words elicited similar networks, activations in response to neutral words were significantly greater in right middle frontal gyrus as revealed by a paired-samples t-test between neutral and negative TBF > TBR contrasts. Moreover, these results were replicated in the second experiment (see Supplementary materials for details).

Table 1
Memory performance as a function of instruction and valence.

	Neutral words	Negative words
TBR	0.78 (0.11)	0.79 (0.08)
TBF	0.44 (0.15)	0.56 (0.16)

3.2.3. Intentional forgetting versus incidental forgetting

Next, we sought to isolate brain regions that could dissociate the processes involved in intentional forgetting and incidental forgetting. For neutral words, intentional forgetting (compared to incidental forgetting) was associated with greater activations in right middle frontal gyrus, consistent with the hypothesized involvement of right prefrontal cortex in intentional forgetting. In contrast, incidental forgetting was associated with activations in left inferior- and middle-frontal gyri, and left precuneus compared with intentional forgetting (Fig. 3, Table 4). Interestingly, for negative words, intentional forgetting (compared to incidental forgetting) did not reveal any significant activation, suggesting that participants may not have been able to effectively engage the inhibition mechanism to implement the intention to forget. Incidental forgetting, on the other hand, was associated only with activation in left inferior frontal gyrus (Fig. 3, Table 4). More importantly, these results were validated by the second experiment (for details, see Supplementary materials, Table S2).

4. Discussion

The current study explored the mechanisms underlying directed forgetting for emotionally negative and neutral words, and investigated whether the efficacy of directed forgetting varied with the emotional valence of the memory to be forgotten. Using the item-method directed forgetting paradigm, we found that although all types of material could be forgotten, people showed significantly less directed forgetting for emotional items compared with neutral items. These results are consistent with some prior evidence suggesting that forgetting emotional

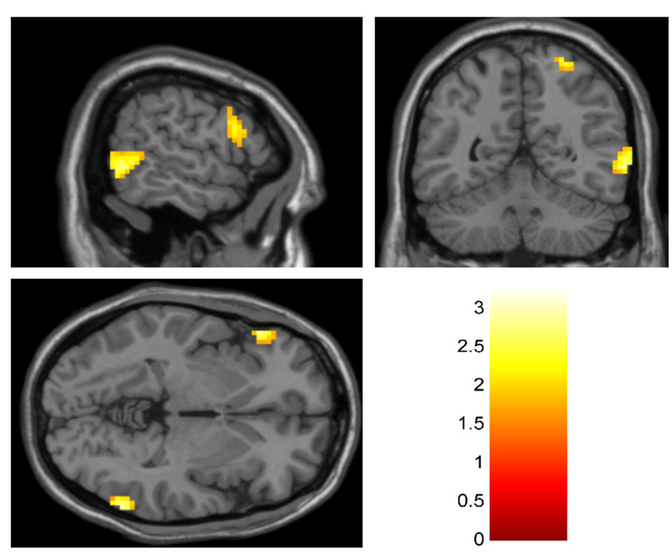

Fig. 1. Activations associated with negative words in comparison with neutral words during words viewing (Negative > Neutral).

[1] The bin sizes of TBF_Forget and TBR_Forget were remarkably small, so the contrast between intentional forgetting and incidental forgetting was potentially underpowered and possibly unreliable.

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Table 2
Regions associated with negative words contrasted with neutral words during words viewing.

Contrast	BA	X	Y	Z	t	Voxels
Negative > Neutral						
L inferior frontal gyrus	47	−54	27	0	3.09	100
R middle temporal gyrus	37	63	−57	−3	2.79	93
R inferior frontal gyrus	45	63	12	21	2.30	56
R superior parietal lobule	7	21	−60	66	3.26	46

memories may be harder than forgetting neutral memories (Barnier et al., 2007; Devilly et al., 2007; Nowicka et al., 2010). At the neural level, the present study revealed three main findings. First, during words viewing, negative words elicited enhanced activations in inferior frontal gyrus, middle temporal gyrus and superior parietal lobule compared with neutral words. Second, TBF instructions for both neutral and negative words were associated with activations in frontal and parietal cortex, reflecting active inhibitory processing. Third, intentional forgetting was associated with inhibition-related regions (right middle frontal gyrus), whereas incidental forgetting was associated with encoding-related regions (left inferior frontal gyrus).

When participants viewed the words, negative words yielded greater activations in bilateral inferior frontal gyrus, together with activations in right middle temporal gyrus and right superior parietal lobule, in comparison with neutral words. Increased activations in left inferior frontal gyrus and right middle temporal gyrus have been linked to encoding-related activities (Gabrieli et al., 1998; Martin, 1999; Shallice et al., 2008b; Squire and Zola-Morgan, 1991), and increased activations in right inferior frontal gyrus and right superior parietal lobule have been implicated in attentional orienting (Corbetta and Shulman, 2002; Shallice et al., 2008a). Taken together, these previous findings suggest that the content of negative words may have captured participants' attention (Brandt et al., 2013; Hauswald et al., 2011; Yang et al., 2012), potentially contributing to more sustained encoding (Fox et al., 2001). This sustained encoding may have led to more durable memories that are harder to forget. However, although this account is plausible, the present findings provide only mixed evidence for it: whereas overall recall was better for negative (mean = 0.67) than for neutral words (mean = 0.61), suggesting superior memory for emotional information, this effect was driven exclusively by superior memory for negative TBF words compared with neutral TBF words, with no apparent difference in the recognition of negative and neutral TBR words. If negative affect generally enhanced memory, one would expect to have found superior memory of TBR items, which we did not observe. This suggests that

Table 3
Regions associated with the intention to forget for neutral and negative words.

Contrast	BA	X	Y	Z	t	Voxels
Neutral words						
TBF > TBR						
R middle frontal gyrus	10	33	57	6	3.73	421
R superior frontal gyrus	6	21	15	66	3.85	74
R inferior parietal lobule	40	57	−45	36	4.09	283
R Precuneus	7	12	−72	36	3.58	155
R middle temporal gyrus	39	45	−54	9	4.13	509
L fusiform gyrus	19	−24	−72	−6	4.21	694
Negative words						
TBF > TBR						
R middle frontal gyrus	9	36	33	39	3.49	78
L superior frontal gyrus	10	−27	54	18	3.33	78
R inferior parietal lobule	40	57	−42	36	4.11	288
R precuneus	7	6	−72	36	4.23	93
R fusiform gyrus	37	33	−66	−12	3.40	80

BA = Brodmann's area; t = statistical t values; R = right; L = left.

superior encoding of emotional items may not be the correct account of the diminished directed forgetting effect for negative items. Instead, enhanced activities in right inferior frontal gyrus and superior parietal lobule during words viewing may reflect the capture of attention by negative content, which may have undermined subsequent processing of the TBF cues, to some extent (Brandt et al., 2013; Hauswald et al., 2011; Yang et al., 2012).

Overall, we found, like prior studies, that the intention to forget an item led to significantly greater engagement of right prefrontal cortex and right inferior parietal lobule, along with a network of other regions (such as fusiform gyrus and precuneus). The right prefrontal cortex and right inferior parietal lobule have been consistently implicated in the item-method directed forgetting, and in other paradigms such as the think/no-think procedure (Anderson and Hanslmayr, 2014), as being important to inhibitory control over memory. Additionally, effective and functional connectivity analyses of both the item-method directed forgetting (Rizio and Dennis, 2013) and retrieval suppression (Benoit and Anderson, 2012; Benoit et al., 2014; Depue et al., 2015; Gagnepain et al., 2014) have revealed clear evidence of top-down negative modulation of the hippocampus (associated with memory function) by the prefrontal cortex. In addition to increased activities in frontal and parietal cortex, TBF cues following negative and neutral words also elicited increased activities in fusiform gyrus and precuneus. These activations may reflect the process of visualization/imagination of TBF items. Since the fusiform gyrus has been shown to be involved in visual

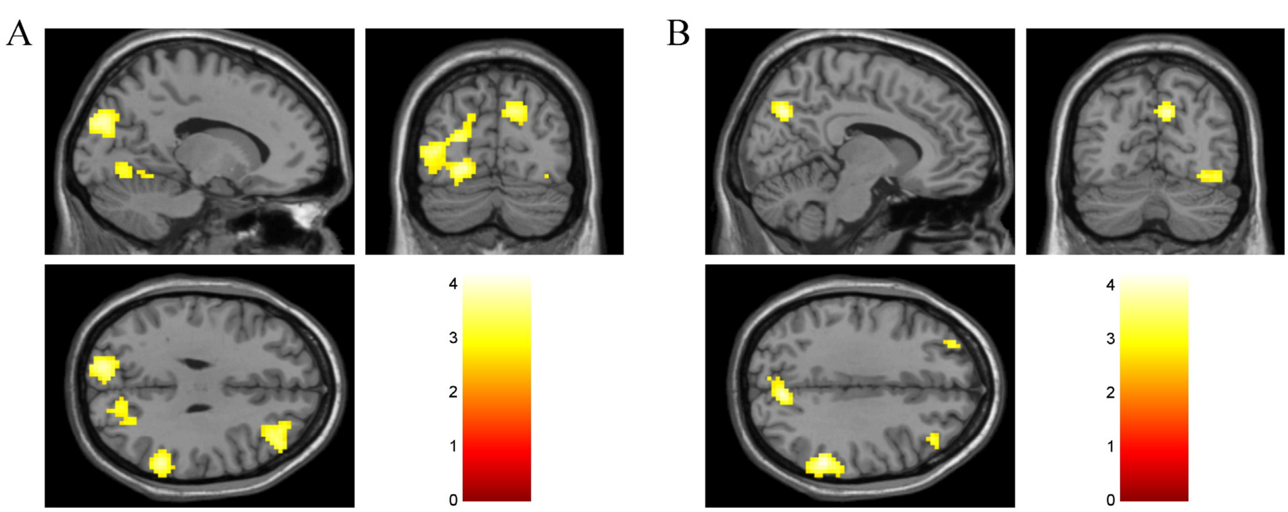

Fig. 2. (A) Areas that are significantly more active for the intention to forget contrasted with the intention to remember (TBF > TBR) for neutral words; (B) areas that are significantly more active for the intention to forget contrasted with the intention to remember for negative words.

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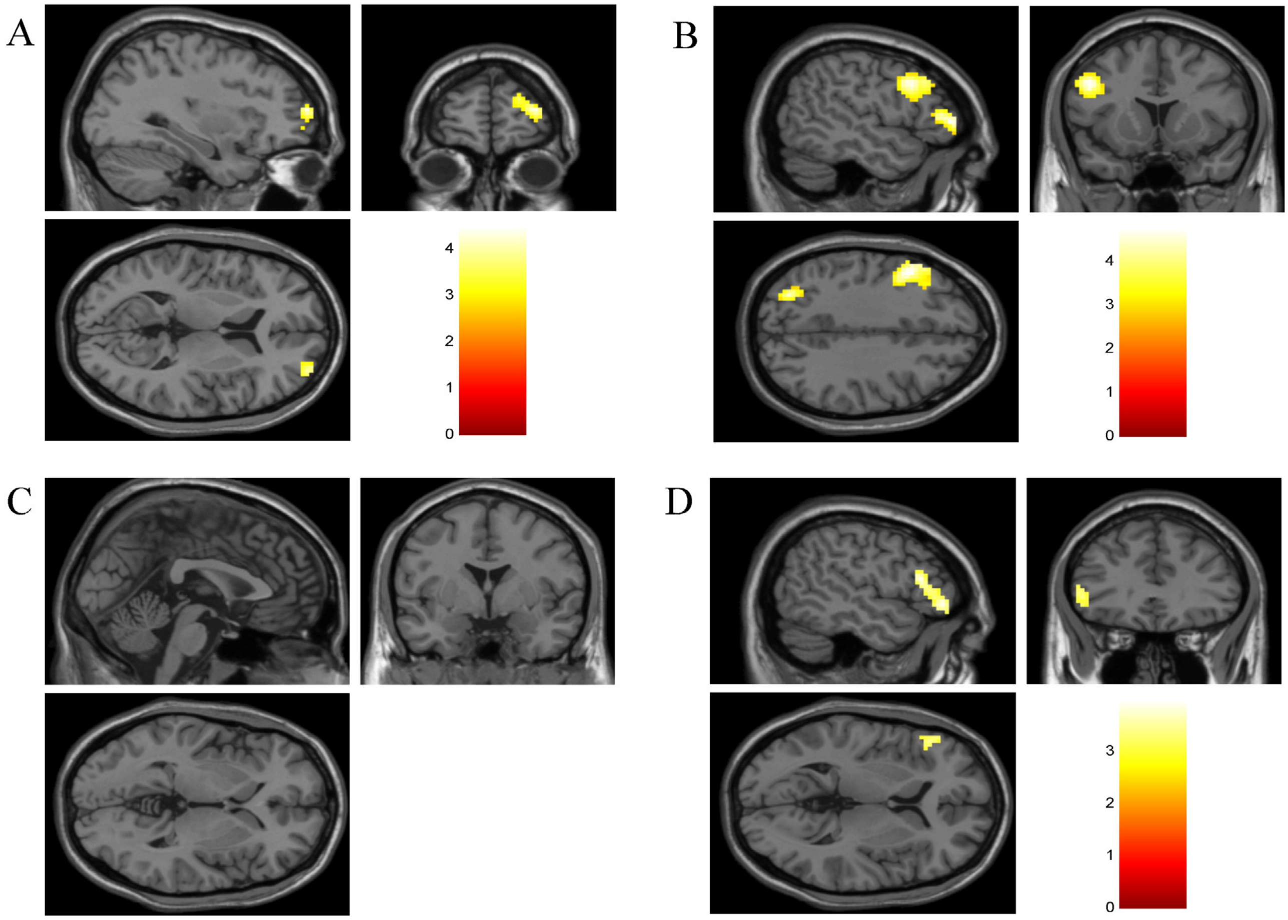

Fig. 3. (A) Areas that are significantly more active for intentional forgetting than incidental forgetting for neutral words; (B) areas that are significantly more active for incidental forgetting than intentional forgetting for neutral words; (C) areas that are significantly more active for intentional forgetting than incidental forgetting for negative words; (D) areas that are significantly more active for incidental forgetting than intentional forgetting for negative words.

processing (Tallon-Baudry et al., 2005) and the precuneus has been found to be associated with internal imagery (Burgess et al., 2007; Cavanna and Trimble, 2006; Kim, 2011; Knauff et al., 2003), the TBF instruction might initiate not only the process of inhibitory control but also visualization/imagination of TBF items. Namely, when receiving the TBF instructions, subjects may engage in imagination-related processing of TBF items in order to ensure which item was asked to be forgotten.

However, although the attempts to forget both negative and neutral memories engaged similar right prefrontal regions, emotional items yielded little evidence of right prefrontal cortex engagement in contrast with neutral items when we focused our analysis not merely on the intention to forget, but rather on the dissociation between intentional forgetting and incidental forgetting. This suggested that inhibitory processing was disrupted for negative items. Theoretical accounts suggest that emotional stimuli, especially negative stimuli, can easily capture participants' attention, an effect known as negative bias (Carretié et al., 2001, 2009; Fox et al., 2001). Due to the attentional bias in processing negative words, inhibitory control for negative words may be weakened, and hence become less effective.

Additionally, it is widely believed that intentional forgetting involves active inhibitory processes, whereas incidental forgetting results from a failure of encoding (Basden et al., 1993; Rizio and Dennis, 2013). In the current study, we found that intentional forgetting was associated with greater activations in right middle frontal gyrus, and this region has been interpreted as reflecting inhibitory processing (Anderson et al., 2004; Hedden and Gabrieli, 2010). For example, Hedden and Gabrieli (2010) found that tasks requiring the inhibition of a motor action relied on activations of right middle frontal gyrus, suggesting a reliable role in tasks involved in inhibitory processing. Anderson et al. (2004) also reported increased activations in right middle frontal gyrus when people needed to inhibit memory retrieval. However, compared with intentional forgetting, incidental forgetting was associated with increased activations in left inferior frontal gyrus and left middle frontal gyrus, which have been associated with encoding attempt, regardless of a memory outcome (Okado and Stark, 2003; Rizio and Dennis, 2013; Slotnick and Schacter, 2006). As such, when a cue to remember appeared, subjects may have engaged in encoding-related activities, but

Table 4
Comparison between intentional and incidental forgetting for neutral and negative words.

Contrast	BA	X	Y	Z	t	Voxels
Neutral words						
TBF_Forget > TBR_Forget						
R middle frontal gyrus	11	42	42	−12	3.91	48
R middle frontal gyrus	10	33	60	12	4.25	59
L postcentral gyrus	1	−21	−30	75	4.46	99
TBR_Forget > TBF_Forget						
L inferior frontal gyrus	46	−51	42	3	4.73	91
L middle frontal gyrus	9	−48	15	36	4.64	234
L precuneus	7	−30	−72	36	4.34	123
Negative words						
TBF_Forget > TBR_Forget						
N/A						
TBR_Forget > TBF_Forget						
L inferior frontal gyrus	45	−54	24	15	3.96	118

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the amount of encoding may not have been sufficient to result in an enduring memory for the item. In addition to increased activities in left inferior and middle frontal gyri, precuneus was significantly more active for incidental forgetting compared with intentional forgetting. This region has been described as an important part of the default mode network (DMN), and is assumed to contribute to mind wandering (Burgess et al., 2007; Kim, 2011; Rizio and Dennis, 2013). Since the DMN and mind wandering have been characterized as involving a shift of attention from the external world to the internal world of a subject (Fox et al., 2015; Kim, 2011), this shift towards internal thoughts may diminish the encoding of external stimuli for items that were incidentally forgotten. Interestingly, however, regions (i.e., precuneus) associated with mind wandering were activated only for neutral words. The lack of activation for negative words may have arisen from the salience of negative items, which may have been harder to ignore, and may therefore have led to a decreased shift of attention towards inner thoughts.

In sum, the present study revealed that the intention to forget negative and neutral words was associated with the active inhibition of TBF words. However, our results suggest that forgetting emotionally negative words may have been harder due to attentional bias during words viewing and decreased inhibitory control during cues presentation. In addition, our results also indicated that intentional forgetting and incidental forgetting for both negative and neutral words were mediated by two distinct neural processes. Intentional forgetting was associated with active inhibition, whereas incidental forgetting was associated with failed encoding. The present results concerning directed forgetting of emotional memories may be informative in understanding difficulties in clinical populations for whom difficulty forgetting unpleasant experiences is a hallmark symptom.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijpsycho.2015.09.007.

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