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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 may be harder to forget emotional information. By means of fMRI, this question was investigated in the item-method directed forgetting paradigm. Behavioral results demonstrated that although all kinds of material could be forgotten, negative words showed reduced directed forgetting effect. At the neural level, the initial viewing of negative words elicited increased activities in inferior frontal gyrus and superior parietal lobule when contrasted with neutral words, which reflected the capture of attention by negative content. Forgetting instructions for negative and neutral words led to enhanced 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

Former studies have suggested that emotion can enhance memory (Phelps and Sharot, 2008). Importantly, the benefits for emotional information have been documented with plenty of material, including pictures and words (Brandt et al., 2013; 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, which can ensure that current memory process is free from irrelevant information (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. Importantly, the paradigm takes two forms: item-method and list-method (Basden and Basden, 1998; Bjork, 1989; Macleod, 1999). For the item-method, participants view a succession of items, followed by an instruction of to-be-forgotten (TBF) or to-be-remembered (TBR) for each of them. For the list-method, the items include two parts. For the first part, fifty percent of the participants are asked to remember these items, while the remaining fifty percent are required to forget these items. Then, the participants study the second list, which is followed by a surprise final test for the original list. In both paradigms, there will be a prominent directed forgetting effect, if memory performance of TBF items is significantly lower in contrast to TBR items.

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, the items are put into working memory before memory instructions appear. TBR instructions are proposed to

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make participants elaborately encode the items, whereas TBF instructions lead participants to drop the items from working memory and not to elaborately encode them. In contrast, the attentional inhibition hypothesis emphasizes that TBF instructions elicit inhibitory control processing that interrupts deeper encoding of the items. In the list-method, the retrieval inhibition mechanism is proposed to account for the directed forgetting effect (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 both selective rehearsal and attentional inhibition are thought to play important roles in supporting the item-method directed forgetting, the item-method gives us the chance to investigate not only encoding process but also inhibitory control process. Additionally, there are only some successful TBF and TBR items, so the item-method also enables us to study the intentional forgetting (TBF items have been forgotten successfully) and incidental forgetting (TBR items have been remembered successfully). Considering these advantages of the item-method, the focus of the study is on 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). Additionally, fMRI studies using the item-method show that TBF instructions, contrasted with TBR instructions, 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).

Recently, researchers have started to investigate the emotional information forgetting. Importantly, studies about clinical patients have shown consistent results that forgetting emotional memories is harder (Joormann et al., 2005; Patrick and Christensen, 2013; Tolin et al., 2002). 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 memories were free from 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. By means of the item-method procedure, Brandt et al. (2013); Hauswald et al. (2011) and Yang et al. (2012) consistently found that TBF instructions elicited increased frontal positivities relative to TBR instructions, suggesting the engagement of an active forgetting process that may inhibit TBF items. However, inconsistencies exist among these ERP studies. Whereas Brandt et al. (2013) and Hauswald et al. (2011) found that the frontal activities elicited by TBF instructions 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.

Till now, however, only one fMRI study has explored the neural basis of emotional information forgetting. For that investigation, 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 successful TBF items with unsuccessful TBR items) 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 for the item-method directed forgetting procedure.

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). Rizio and Dennis (2013) and Wylie et al. (2008) reported evidence indicating that the neural processes of intentional forgetting and incidental forgetting were different for neutral information. Specifically, intentional forgetting, relative to incidental forgetting, elicited 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 related to the employment of left inferior frontal gyrus involving in encoding. Critically, however, existing studies have not fully differentiated intentional forgetting from 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.

For the present study, the neural substrates underlying directed forgetting of emotionally negative and neutral information were investigated by use of the item-method directed forgetting procedure. At the behavioral level, we speculated that there would be a prominent directed forgetting effect for negative and neutral information. 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. Materials and methods

2.1. Participants

Twenty-one right-handed, healthy undergraduate students of Southwest University between the ages of 18–25 years (average age: 22.19; 13 females) took part in and finished this experiment for monetary compensation. All of the participants were native Chinese speakers without psychiatric disease, and they have normal or corrected-to-normal vision. Each participant provided the written informed consent to participate in this experiment, 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 valence ($F(1130) = 1521.95$, $P < 0.001$) and arousal ($F(1130) = 21.64$, $P < 0.001$) of these two kinds of nouns were different, but the frequency ($F(1130) = 0.06$, $P = 0.810$) and familiarity ($F(1130) = 0.76$, $P = 0.388$) were matched. All nouns were separated into two parts, and each part included 32 negative and 32 neutral words. One part was chosen to be study items, whereas the remaining one was chosen to be the interferences. These nouns in the two parts 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. During the study stage, each participant viewed 36 neutral words and 32 negative words. After one word was exhibited for 1500 ms, a 1000 ms presentation with a fixation cross was shown. 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 among trails, but each kind of postcue length had the same probability. Importantly, fifty percent of the neutral nouns and fifty percent of the negative nouns were marked as TBR, whereas the remaining nouns were marked as TBF. Additionally, all trials were shown in a pseudo-random order, with the restriction that less than three successive trials had the same kind of valence and memory instruction.

In the test phase, all the 128 nouns were shown in a pseudo-random order, with the restriction that less than three successive trials had the same kind of stimulus (old or new). One word was exhibited for 2500 ms. For the mean time, participants had to perform an old-new recognition test as quickly and accurately as possible, irrespective of the previous TBR or TBF instructions.

2.3. Imaging

Imaging was performed using a 3 T Siemens Trio scanner with an eight-channel phased array coil. A vacuum cushion was used to minimize the head movement. Participants viewed words from the back-projection screen using an angled mirror mounted on the head coil.

301 functional volumes were obtained by use of a T2-weighted gradient echo planar imaging (EPI) sequence (TR = 1500 ms, TE = 29 ms, axial slices = 25, thickness/gap = 5/0.5 mm, FOV = 192×192 mm^2, voxel sizes = $3 \times 3 \times 3$ mm^3, matrix size = 64×64, flip angle = 90°). Furthermore, the high-resolution T1-weighted structural images were collected after the functional scans (TR = 1900 ms, TE = 2.52 ms, voxel size = $1 \times 1 \times 1$ mm^3, FOV = 256×256 mm^2, matrix size = 256×256, 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. By measuring the percentage of studied items correctly recognized in each condition, we examined whether there was a prominent directed forgetting effect for emotionally negative and neutral words. Hence, memory performances of TBR and TBF words were calculated by repeated-measures ANOVAs with type of memory 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 by use of SPM8 (http://www.fil.ion.ucl.ac.uk/spm). First, functional data of each participant were corrected for acquisition timing delays and for head motion. Second, the high-resolution structural T1 images from each participant were coregistered to the mean functional images. Third, the unified normalization routine was conducted with voxel size $3 \times 3 \times 5$ mm^3. Finally, an 8-mm Gaussian kernel at full-width half-maximum was used to perform data smoothing.

Data analyses were carried out by using a general linear model. Specifically, the brain activations associated with separate event types were obtained with the general linear model. Each event was modeled to the onset of each word or the TBR/TBF instruction, and each trial was thought to be a separate event (duration = 0). Furthermore, six head-movement regressors were also involved 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. Then, the contrast images were further processed with 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, and Neutral_TBF. These four conditions were all modeled at the onset of the TBR or TBF instruction. Then these four conditions from the individual participants were analyzed with a full factorial analysis to assess the brain activations underlying directed forgetting of neutral and negative 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, the goal of the present study was to explore the brain mechanisms related to directed forgetting for emotionally negative and neutral memories, so we also modeled additional conditions according to the combination of memory cues (TBR/TBF) and the later memory performance (Remembered/Forgotten) for negative and neutral words separately. In particular, we defined four new conditions in which we focused on the subsequently forgotten items from each of our main conditions: TBF_Forget_Negative, TBR_Forget_Negative, TBF_Forget_Neutral, and TBR_Forget_Neutral. These four conditions were all modeled at the onset of TBR or TBF instruction. With these four conditions, we examined whether intentional forgetting and incidental forgetting were two different neural processes based on the

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)

comparison of TBF_Forget condition and TBR_Forget condition for negative and neutral words separately.

The AlphaSim program was used to carry out the multiple comparison correction (Yan and Zang, 2010). In this study, by combining an individual voxel threshold of $P < 0.005$ and a cluster size of 46 contiguous voxels, a corrected threshold of $P < 0.05$ was gained. 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, Table S1 and Table S2).

3. Results

3.1. Behavioral results

The results of repeated-measures ANOVAs were shown in Table 1. The memory performance of TBR words was significantly greater contrasted with TBF words ($F(1,20) = 76.29$, $P < 0.001$). The recognition scores of negative words were greater in comparison with neutral words ($F(1,20) = 12.54$, $P < 0.01$). Additionally, a significant interaction ($F(1,20) = 8.98$, $P < 0.01$) between memory instruction and valence indicated that negative words ($F(1,20) = 76.63$, $P < 0.001$) and neutral words ($F(1,20) = 40.16$, $P < 0.001$) could be successfully forgotten, but 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 superior parietal lobule and right middle temporal gyrus, whereas there were no activation for neutral words in contrast with 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 prominent activations in right middle frontal gyrus, right superior frontal gyrus, 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

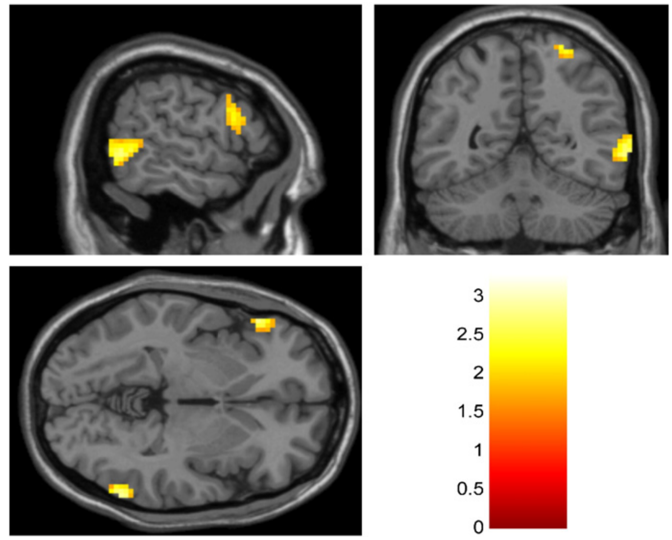

Fig. 1. Activations associated with negative words in comparison with neutral words during words viewing (Negative > Neutral).

activations included the 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).

3.2.3. Intentional forgetting versus incidental forgetting

Next, we sought to isolate brain regions that could demonstrate that intentional forgetting and incidental forgetting were two different neural processes. For neutral words, intentional forgetting, compared to incidental forgetting, elicited enhanced activations in right middle frontal gyrus, consistent with the hypothesized involvement of right prefrontal cortex in intentional forgetting. In contrast, incidental forgetting led to increased activations in left middle frontal gyrus, left inferior frontal gyrus, 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, however, only resulted in enhanced activities 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).

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

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

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

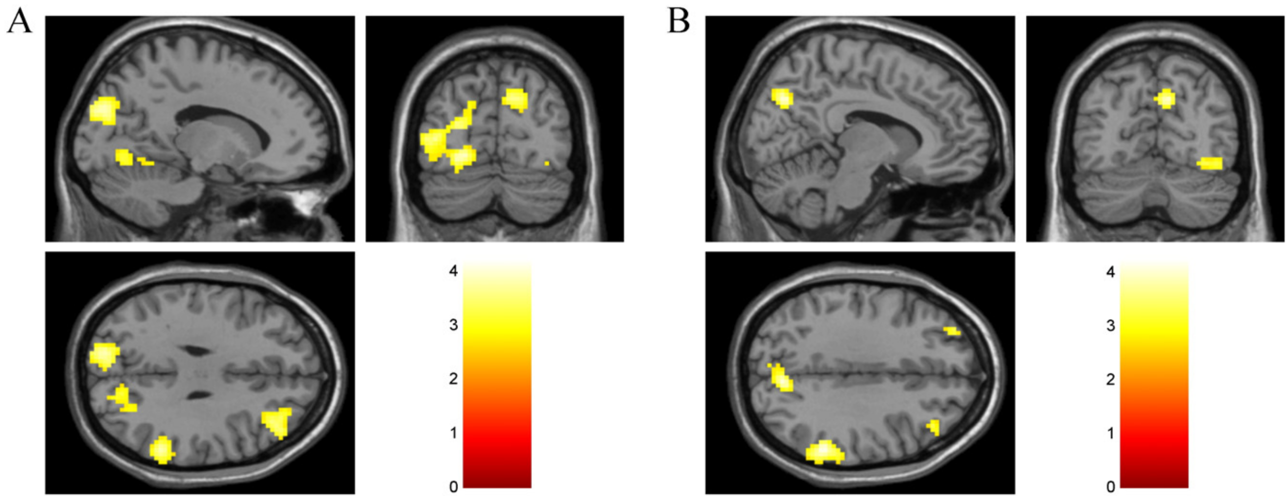

Fig. 2. (A) Brain areas with enhanced activations for TBF instructions in comparison with TBR instructions for neutral words; (B) Brain areas with enhanced activations for TBF instructions in contrast with TBR instructions for negative words.

4. Discussion

The present study investigated the neural basis underlying directed forgetting of neutral and negative words, and examined 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 negative words relative to neutral words. These results are consistent with some prior evidence suggesting that forgetting emotional memories may be harder than forgetting neutral memories (Barnier et al., 2007; Devilly et al., 2007; Nowicka et al., 2010). At the neural level, three main findings were found. First, during words viewing, negative words elicited enhanced activations in bilateral inferior frontal gyrus, right superior parietal lobule and right middle temporal gyrus in comparison with neutral words. Second, TBF instructions for both neutral and negative words led to increased activities 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 related to encoding-related regions (left inferior frontal gyrus).

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.

When participants viewed the words, negative words yielded greater activations in bilateral inferior frontal gyrus, together with activations in right superior parietal lobule and middle temporal gyrus, 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). In conclusion, the former findings suggest that the content of negative words may have captured participants' attention (Brandt et al., 2013; Hauswald et al., 2011), 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 between negative TBR words 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 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).

Overall, we found, like prior studies, that the intention to forget an item led to significantly greater engagement of right prefrontal cortex and inferior parietal lobule, along with a network of other regions (such as fusiform gyrus and precuneus). The right prefrontal cortex and inferior parietal lobule have been consistently thought to be involved in the item-method directed forgetting, and in other paradigms (i.e., 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;

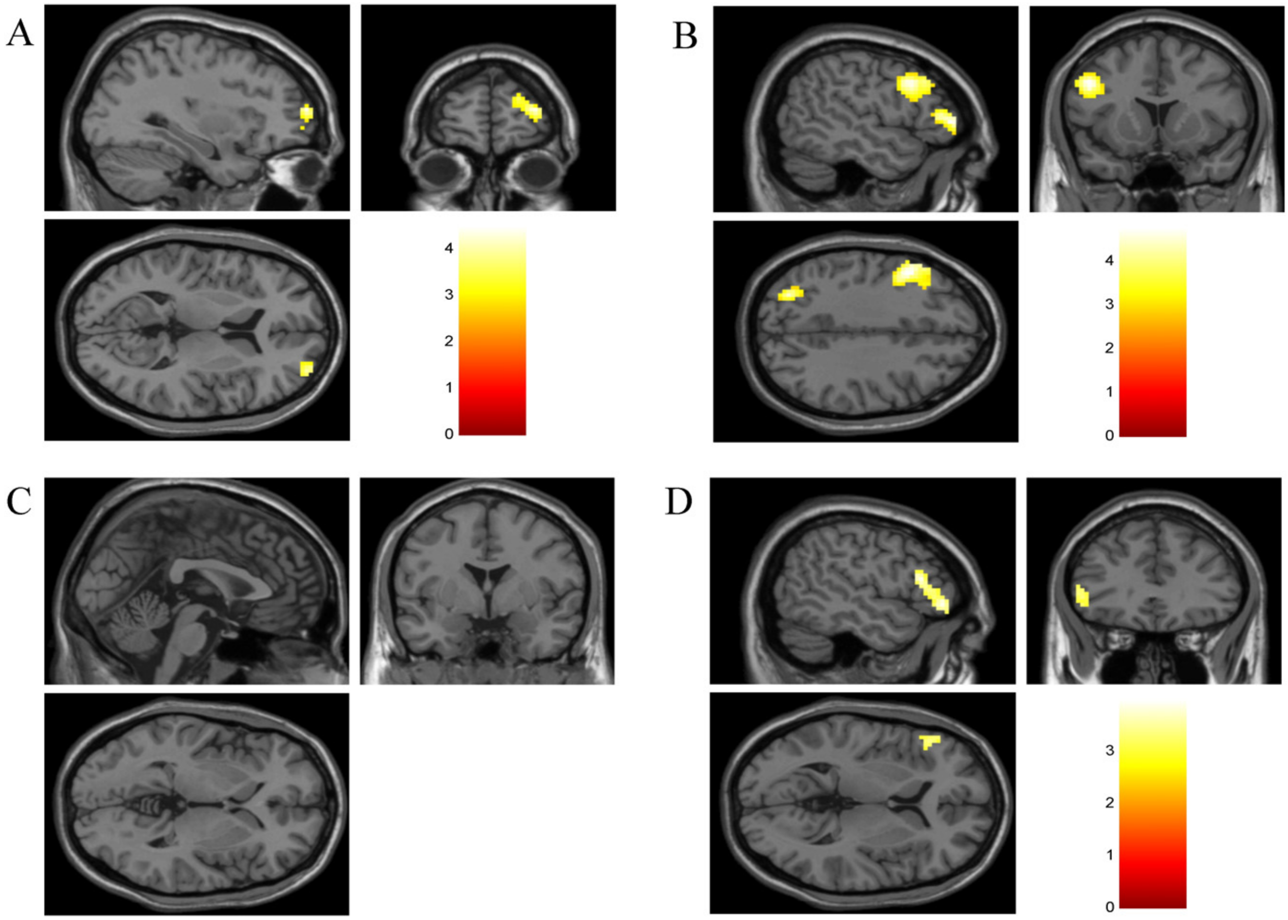

Fig. 3. (A) Brain regions showing increased activities for intentional forgetting in contrast to incidental forgetting for neutral words; (B) Brain regions showing increased activities for incidental forgetting in comparison to intentional forgetting for neutral words; (C) Brain regions showing increased activities for intentional forgetting in contrast to incidental forgetting for negative words; (D) Brain regions showing increased activities for incidental forgetting in comparison to intentional forgetting for negative words.

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 imagination process. Since fusiform gyrus has been thought to be implicated in visual processing (Tallon-Baudry et al., 2005) and 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 instructions might employ not only the inhibitory control process but also the imagination process. Namely, when given the TBF instructions, participants might engage in imagination-related processing of TBF items in order to ensure which item was asked to be forgotten.

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

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

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 separation of intentional forgetting and incidental forgetting. This suggested that the inhibitory control process 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., 2009; Fox et al., 2001). Because of 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 in active inhibitory processes, while incidental forgetting is due to failed encoding (Basden et al., 1993; Rizio and Dennis, 2013). In the current study, we found that intentional forgetting elicited greater activations in right middle frontal gyrus. Importantly, this region has been interpreted as reflecting inhibitory processing

(Anderson et al., 2004; Hedden and Gabrieli, 2010). For example, Anderson et al. (2004) reported increased activations in right middle frontal gyrus when people needed to inhibit memory retrieval. However, compared with intentional forgetting, incidental forgetting led to increased activations in left middle and inferior frontal gyri, which have been associated with encoding attempt, in spite 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 the amount of encoding may not have been sufficient to result in an enduring memory for the item. Apart from enhanced activations in left inferior and middle frontal gyri, incidental forgetting also resulted in stronger activations in precuneus. This region has been described as an important part of default mode network (DMN), and is thought 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 information. The lack of activation for negative information may be due to the salience of negative information, 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 inhibitory control processing, while incidental forgetting was due to 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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