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Research Report

Different neural substrates underlying directed forgetting for negative and neutral images: An event-related potential study

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ABSTRACT

The aim of this study was to investigate the different neural correlations of directed forgetting for emotionally negative and neutral images in 17 healthy individuals using event-related potentials (ERPs). Behavioral findings showed that the task yielded a robust directed forgetting effect for both neutral and negative images: more to-be-remembered than to-be-forgotten images were recognized. ERPs were recorded as participants viewed different valence images (negative/neutral) and were given different instructions, including remember (R) or forget (F) commands. Enhanced late parietal positive potentials were observed for negative images during image viewing. In the 200–300 ms time window, F instructions elicited a larger N2 than did R instructions and successful implementation of F instructions (F-miss) appeared more negative over the frontal region comparing with the unintentional forgetting (R-miss), suggesting that F instructions trigger a frontal mechanism to inhibit the processing of previously presented images. More important, F instructions following emotionally negative images elicited an enhanced frontal N2 effect than neutral images. This result suggests that forgetting negative stimuli is more laborious. In addition, within the 300–400 ms time window, R instructions elicited a larger P3 response than did F instructions and successful implementation of the R instructions (R-hit) appeared more positive than the unintentional remembering (F-hit) over the posterior scalp region. This posterior wave might reflect rehearsal and memory consolidation process.

1. Introduction

In daily life, it is important to set aside irrelevant information out from the mind and turn to focusing on current tasks. This everyday demand for memory control has been studied in laboratories using the directed forgetting and think/no-think (TNT) paradigm. Commonly there are two common variants of the directed forgetting paradigm: the item and list methods (Basden et al., 1993). Item method directed forgetting is the paradigm of interest in the present investigation. In this method, participants are asked to follow an instruction, either "remember" (R) or "forget" (F), after the presentation of each item. In the list method, participants are presented with a list of words that they are told to remember for later testing. Halfway through the list, however, a surprise instruction to forget the preceding words is given. A directed forgetting

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effect is obtained when items instructed to be forgotten remembered worse than items those which are instructed to be remembered during the test phase. The recently developed TNT paradigm is a memory adaptation of the go/no-go task, which is typically used to study the control of prepotent motor response. In the TNT paradigm, participants study word pairs and are trained to answer with the appropriate associate (target) upon presentation of its counterpart (cue). After the training, participants engage in a TNT task. The cue word is provided and participants are required to either remember (think) or actively suppress (no think) images of the corresponding target. Results of later memory tests indicate that the no-think phase inhibits memory for the learned word pairs, so that the no-think pairs are less easily remembered than even unpracticed pairs (Anderson and Green, 2001; Anderson et al., 2004).

Although the explanations for the mechanism of different paradigms are inconsistent, many experts hold that the ability to control memory is analogous to controlling overt behavior, inhibitory control mechanisms are important in this process (Bauml et al., 2010; Depue et al., 2006; Hourihan and Taylor, 2006; Levy and Anderson, 2008). These viewpoints are favored by both behavioral and neuro-scientific studies (Bergstrom et al., 2007; Hanslmayr et al., 2009; Levy and Anderson, 2008; Wylie et al., 2008; Zacks et al., 1996). Evidence suggest that forgetting in the TNT paradigm results from interference (Hertel and Calcaterra, 2005; Tomlinson et al., 2009), but many electrophysiological activities indicate that forgetting during NT trials is caused by the inhibitory control mechanism (Anderson and Green, 2001; Anderson et al., 2004; Depue et al., 2007; Hanslmayr et al., 2009; Mecklinger et al., 2009). Mecklinger et al. (2009) found that NT trials elicited an N2 event-related potential (ERP) component that showed a centro-parietal scalp distribution similar to that observed in successful stopping in a motor stopping experiment, in which a stop signal task was used. The front-central N2 is a negative component with a latency of 200–300 ms after stimulus onset observed in the go/no-go task (Eimer, 1993). In general, N2 is a marker of general inhibitory control (Donkers and van Boxtel, 2004; Eimer, 1993). Results from fMRI studies also favor the inhibitory control findings (Anderson et al., 2004; Depue et al., 2007). Anderson et al. (2004) demonstrated that NT trials were associated with the increased activation of the dorsolateral prefrontal cortex (DLPFC) and decreased activity in the left and right hippocampus. Both activations predicted the magnitude of subsequent forgetting. The deactivation in the right hippocampus was correlated with the increased activity in the DLPFC, suggesting that the DLPFC imposes cognitive control over the hippocampus to keep the unwanted memory from entering the mind. Using emotional pictures rather than words, Depue et al. (2007) also reported increased activation of prefrontal cortex regions and decreased activation of the hippocampus during NT trials. Together, these two studies suggest that suppression in the TNT paradigm is mediated by prefrontal cortex regions, which downregulate the activity in memory-related processing areas to keep unwanted memory from entering consciousness.

Although both the list and item method directed forgetting paradigms result in reduced retrieval of to-be-forgotten (TBF) information, the underlying processes differ slightly. When the item method is used, the selective rehearsal account is generally favored (Basden et al., 1993; MacLeod, 1999; Woodward and Bjork, 1971). This hypothesis suggests that study items are initially maintained in short-term memory with rote rehearsal until the presentation of F/R cues. Rote rehearsal is terminated in response to F instructions, thus, to-be-remembered (TBR) items receive more elaborate rehearsal than do TBF items, thereby contributing to the directed forgetting effect. The selective rehearsal account, however, cannot explain some results in list method directed forgetting. In the latter, participants are initially instructed to remember an entire list of stimuli, but halfway through, a surprise instruction to forget the preceding words is given. Hence, all the items have been deeply encoded. Furthermore, recognition and indirect memory tests do not show directed forgetting, suggesting that the items are available in memory but are simply inaccessible (Basden et al., 1993; Bjork and Bjork, 1996). According to this perspective, an inhibitory mechanism is invoked at the time of retrieval. This invocation reduces access to unwanted memories, producing lower recall of list 1 items. On re-exposure of stimuli during recognition tests, the retrieval inhibition is released, thereby yielding no directed forgetting effect in recognition tests.

In recent years, much behavioral and neuropsychological evidence has challenged the standard selective rehearsal account of item method directed forgetting. Studies suggest that attentional inhibition during encoding process may be critical to item method directed forgetting. Such inhibitory processes may simply terminate the rehearsal of TBF items or suppress their memory activation to below baseline levels (i.e., representational inhibition) (Levy and Anderson, 2002). This theory argues that study items are initially maintained in short-term memory with rote rehearsal until the presentation of F/R instructions. After instructions a period should follow, the receipt of an F instruction causes attention to be withdrawn from TBF items, which are prevented from returning to their representations, so that adequate working memory resources can be released for the enhanced rehearsal of TBR items (Hasher and Zacks, 1988; Zacks et al., 1996). Zacks et al. (1996) found that older adults, who generally showed insufficient inhibitory control, exhibited a smaller directed forgetting effect than did young adults. Hourihan and Taylor (2006) found that intentional forgetting may engage cognitive control processes at overt encoding that is analogous to that required to prevent the execution of prepotent overt response. Evidence from ERP studies suggest that both inhibitory control theory and selective rehearsal contribute to directed forgetting (Hsieh et al., 2009; Paz-Caballero and Menor, 1999; Paz-Caballero et al., 2004). These studies found that different processes were elicited by R and F instructions: R instructions evoked enhanced positive-going component in the temporal or posterior regions while F instructions evoked frontal or prefrontal activity. The initial effect pointed to the differential rehearsal hypotheses for the directed forgetting effect, while the later effect reflected the hypotheses of inhibition account. In order to make a fuller understanding of the episodic memory encoding in DF paradigms, some studies compared the ERPs of the R and F instructions associated with the subsequent memory effect (Hsieh et al., 2009; van Hooff and Ford, 2011). Differences between ERPs for items that are successfully remembered and those for items that are incorrectly rejected are known as Dm (Difference in subsequent memory) or subsequent memory effects(Otten and Rugg, 2001). Hsieh et al. (2009) found that the subsequent memory effect elicited by the remember instructions was more sustained than that elicited by the forget instructions and showed distinct scalp distribution during the extended period. Hsieh et al. (2009) examined the process underlying successful implementations of forget instructions and found that a frontal inhibition mechanism was engaged to stop processes associated with intentional memory formation. In conjunction with a recent fMRI study (Wylie et al., 2008), the results suggest that selective rehearsal and frontal control processes may be critical to directed forgetting.

An interesting issue in memory control is whether people can intentionally forget emotional memories. Everyday experience suggests that the ability to control emotional events is limited, and many experiments support that emotional stimuli occur automatically (Bradley et al., 1992; for an overview see: Hamann, 2001). Electrophysiologically, this is reflected in enhanced late parietal positive potentials (LPPs). Neuropsychological evidence also suggests that interactions between the amygdala and hippocampus are critical to this enhancement (Hamann, 2001; Palomba et al., 1997; Phelps, 2004). Though the preferential processing of emotional stimuli, many scientific studies on emotional memory in directed forgetting indicate that people can actively forget emotionally negative memories. A comparison of directed forgetting of pleasant and unpleasant words revealed intentional forgetting of both (Tolin et al., 2002). Similarly, many studies on the clinical populations also found directed forgetting effect using trauma-related (McNally et al., 1998), depression-related words (Dumont, 2000). Some data even suggest more intentional forgetting of negative than neutral memories (Depue et al., 2006).

How do people intentionally control and forget these emotionally dominant stimuli? To the best of our knowledge, only one ERP study thus far has investigated the neural mechanism of the directed forgetting of emotionally negative information (Hauswald et al., 2010). Hauswald et al. (2010) showed that directed forgetting occurred for neutral but not for negative pictures. The ERP data recorded during the presentation of instructions showed larger LPPs for R instructions and enhanced frontal positivity for F instructions. These results indicate that both selective rehearsal and frontally controlled inhibition contribute to directed forgetting. Furthermore, a negative correlation was found between LPP enhancement for negative pictures during viewing and the magnitude of directed forgetting. This result indicates that enhanced pre-cue processing counteracts the directed forgetting effect for negative pictures. However, the behavioral results of the aforementioned studies are inconsistent with previous findings, which suggest that negative words and pictures can be successfully forgotten (Depue et al., 2006; Johansson et al., 2007). Hauswald et al. (2010) explained these differences, stating that the arousal of the negative images differed from that of the neutral images in their study, whereas previous studies matched the arousal and valence of neutral and negative images. The clarification indicates that arousal may be important in eliminating directed forgetting. Because these two previous experiments (Depue et al., 2006; Johansson et al., 2007) used the TNT paradigm, the importance of arousal in eliminating directed forgetting must be examined in the directed forgetting paradigm with equal arousal of negative and neutral images. Accordingly, the arousal of negative and neutral images was matched in our recent study. If the conclusion of Hauswald is correct, that is, the arousal of stimulus materials determines the elimination of directed forgetting, the behavioral results would show that emotionally negative images can be forgotten.

In the current study, we explored the neural mechanisms of directed forgetting for negative and neutral images using high-density (64 channels) ERP recording. On the basis of the recommendations of previous studies, we tested the following assumptions: First, enhanced LPPs that represent the enhanced processing of emotionally negative images should be found during negative image viewing (Bradley et al., 1992; Hamann, 2001). Second, ERPs elicited by instructions might differ. Under the selective rehearsal account and previous ERP studies on directed forgetting, R instructions are predicted to evoke a P3 component representing memory encoding (Azizian and Polich, 2007; Eimer, 1993; Hsieh et al., 2009; Paller, 1990; Paz-Caballero and Menor, 1999; Paz-Caballero et al., 2004; Ullsperger et al., 2000). According to the attentional inhibition theory, on the other hand, F instructions would elicit frontal N2 ERP components representing active inhibitory processing (Donkers and van Boxtel, 2004; Eimer, 1993; Hourihan and Taylor, 2006; Taylor and Ivanoff, 2003). Moreover, because of the preferential processing of negative images, it is a reasonable assumption that participants may pay more substantial cognitive resources to withdraw attention from TBF negative images and actively inhibit them from entering into working memory for deep encoding. Accordingly, we hypothesize that F instructions succeeding emotionally negative images elicit a larger frontal N2 than do neutral images. Finally, we examined the ERP patterns of different instructions associated with the subsequent memory effect. Combined with the former prediction, we expect that the successful implementation of the F instructions might appear more negative over the frontal region compared with the unintentional forgetting (e.g. F-miss vs. R-miss). By contrast, successful implementation of the R instructions would appear more positive than the unintentional remembering over the posterior scalp region (e.g. R-hit vs. F-hit).

2. Results

2.1. *Behavioral results*

Repeated measures ANOVAs were performed over the hit rates of TBR and TBF stimuli, with the types of valence (neutral, negative) and instruction (F, R) as factors. The main effect of the instruction was significant [F (1, 16)=24.059, $P<0.001$], reflecting the hit rate of the TBR items (74.8%±2.4) was greater than that of the TBF items (69.6%±2.1). Furthermore, the main effect of valence [F (1, 16)=8.241, $P<0.05$] showed that the hit rate of the emotionally negative images (76.19%±0.9) was greater than that of the neutral items (68.25%±1.1). No interaction was observed between these two kinds of stimuli.

Considering the recognition biases when only the hit rate was calculated, thus, the repeated measures ANOVAs were performed over the discriminate accuracy (hit-false alarms) and recognition biases (false/1 discrimination). The mean discrimination accuracies and recognition biases are presented in

Table 1 – Means and standard errors (Mean±SE) of response rates for hits and false alarms and the values for discrimination accuracy (Discrimination) and recognition bias (Bias).

	Neutral item		Negative item	
	TBF	TBR	TBF	TBR
False alarms	016±0.14		0.22±0.15	
Discriminations	0.52±0.16		0.54±0.17	
Bias	0.33±0.20		0.48±0.17	
Hits	0.66±0.12	0.71±0.11	0.74±0.10	0.79±0.10

Table 1. Because it was not possible to distinguish the false alarms of each condition (R or F), therefore, we only considered the two levels of the emotional valence factors for analyzing of the discrimination and bias measures. The result only showed a main effect of valence [F (1, 16)=6.432, $P<0.05$] for recognition bias, suggesting that the participants were biased in classifying the negative images as previously presented.

Another repeated measures ANOVA was performed on the reaction time. The main effect of the instruction [F (1, 16)= 5.722, $P<0.05$] revealed that the reaction time of the TBF items (mean=852.243±20.95) was longer than that of the TBR items (mean=838.34±19.65). Furthermore, interaction between instruction and valence occurred [F (1, 16)=13.207, $P<0.05$]. The simple effect analysis reflected the reaction time of the negative images was longer than that of the neutral images succeeding F instructions [F (1, 16)=16.80, $P<0.001$], whereas no difference was observed for R instructions. The results are displayed in Table 2.

2.2. *ERP wave analysis*

2.2.1. *ERP effects during image viewing*

As shown in Fig. 1, the negative images elicited enhanced LPPs compared with the neutral images over parietal brain areas between 400 and 1000 ms after the presentation of images. ANOVA was conducted for LPP, with valence (neutral, negative) and electrode sites as factors. The main effect of valence [F (1, 16)=20.903, $P<0.001$] was that the negative images were more positive (4.576 μV±0.923) than the neutral images (2.118 μV±0.619). Electrode sites also showed a main effect [F (2.044, 32.696)=6.218, $P<0.05$]: pairwise comparison of the primary effects of electrode sites revealed a significant effect between FCz and Cz ($P<0.001$), as well as between FCz and Pz ($P<0.001$).

2.2.2. *Effects of instructions*

During the time window of 200–300 ms, an ANOVA with instruction (F/R), valence (neutral/negative), anterior–posterior caudality, and right–left hemisphere as factors yielded a main effect of instruction [F (1, 16)=7.88, $P<0.05$]. Mean amplitude was more negative for the F instructions (4.386 μV±0.941) than for the R ones (5.565 μV±1.004). Furthermore, interaction between instruction and valence occurred [F (1, 16)=6.441, $P<0.05$]. The simple effect analysis reflected that negative images were more negative (3.876 μV±0.621) than neutral ones (5.952 μV±0.795) under the F condition [F (1, 16)=7.215, $P<0.05$], whereas no difference was observed under the R condition. The interaction between instructions and anterior–posterior caudality was also significant [F (1.160, 18.554)=3.287, $P<0.05$]. The simple effect analysis showed that the effect of instruction was significant over the anterior sites [F (1, 16)=3.435, $P<0.05$], but not over the posterior [F (1, 16)=1.768, $P>0.05$] and central sites [F (1, 16)= 1.287, $P>0.05$]. In addition, interaction among valence, instruction, and anterior–posterior caudality was observed [F (1.668, 26.681)=4.203, $P<0.05$]. The simple effect analysis suggested that the ERP amplitude of the F instructions following the negative images were more negative (2.315 μV±0.952) than those following the neutral images (4.023 μV±1.000) over the anterior scalp region [F(1, 16)=6.721, $P<0.05$] (left side, Fig. 3).

Table 2 – The reaction times (Mean±SE) for correctly classified items in the recognition task (TBF=to-be-forgotten, TBR=to-be-remembered).

	TBR	TBR-R	False alarm
Neural	838.61±75.73	848.28±70.34	866.06±72.31
Negative	865.76±96.62	831.41±91.17	938.34±92.16

In the 300–400 ms time window, the main effect of instruction [F (1, 16)=5.967, $P<0.05$] reflected that R instructions (7.861 μV±0.821) showed more positive than the F ones (6.235 μV±1.012). Moreover, the results also showed a main effect of anterior–posterior caudality [F (1.292, 19.378)=10.967, $P<0.05$], and the interaction between instruction and anterior–posterior caudality [F (1.961, 29.411)=4.624, $P<0.05$]. The simple effect analysis showed that the amplitude of the ERP provoked by the R instructions were more positive than the F ones over the posterior scalp region [F (1, 16)=7.624, $P<0.05$] and central scalp sites [F (1, 16)=5.624, $P<0.05$]. However, no main effect was found for the anterior sites [F (1, 16)=1.624, $P>0.05$]. In addition, interaction among valence, instruction, and anterior–posterior caudality [F (1.125, 16.869)=3.624, $P<0.05$] was observed. The simple effect analysis also revealed that the ERP amplitude of the neutral images were more positive than the negative images under R condition over the posterior scalp sites [F (1, 16)=4.327, $P<0.05$] and central caudality [F (1, 16)= 3.141, $P<0.05$] (right side, Fig. 3).

Subsequently, a three-way repeated measures ANOVA was carried out during the time window of 500–600 ms. The result showed a main effect of anterior–posterior caudality [F (1.670, 26.723)=6.626, $P<0.05$] and the right–left hemisphere [F (1.218, 19.487)=16.626, $P<0.001$].

2.2.3. *Subsequent memory effect × instruction*

ERPs elicited by the F and R instructions were separately averaged according to whether the study images preceding the instructions were correctly identified or incorrectly rejected. For 13 participants, a sufficient number of trials were conducted (>15 trials) for reliable calculation of the ERPs of all eight stimulus-performance categories: neutral TBR-hit (mean=32.2 trials, range: 27–38), neutral TBR-miss (mean=18.4 trials, range: 16–20), negative TBR-hit (mean=34.9 trials, range: 28–36), negative TBR-miss (mean=16.5 trials, range: 15–18), neutral TBF-F (mean=19.1 trials, range: 15–20), neutral TBF-R (mean=31.6 trials, range: 26–36), negative TBF-F(mean=17.7 trials, range: 15–19), and negative TBF-R (mean=33.2 trials, range: 27–35).

A main effect of instruction was found within 200–300 ms [F (1, 12)=6.478, $P<0.05$]. The mean amplitudes were more negative for the F instructions than the R ones. Moreover,

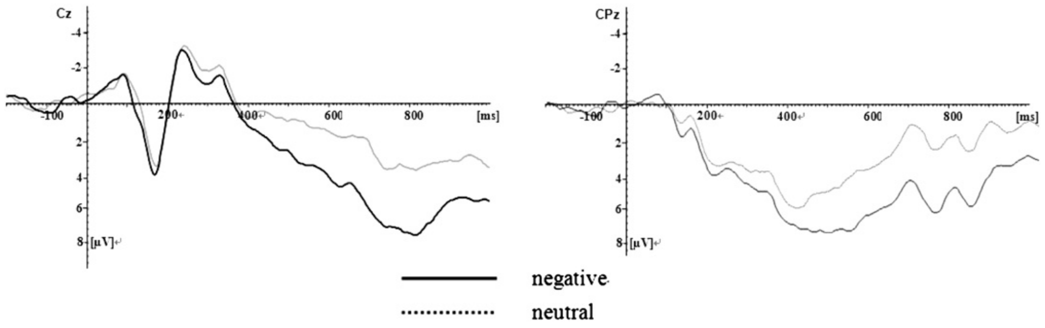

Fig. 1 – Enhanced LPP during the presentation of negative vs. neutral images.

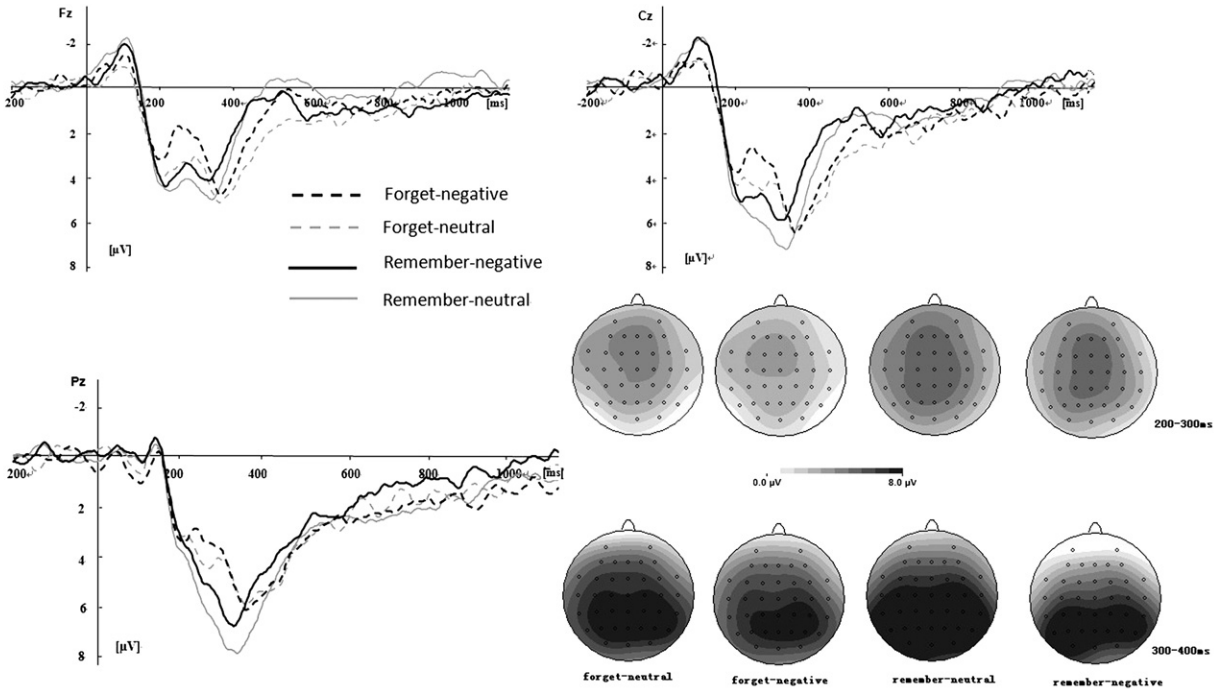

Fig. 2 – Top and bottom left: grand average ERPs at Fz, Cz and Pz for four kinds of instructions. Bottom right: the topographical maps of the voltage amplitudes for four conditions (forget-neutral, forget-negative, remember-neutral, and remember-negative) at 200–300 and 300–400 ms.

the results also showed that interaction between valence and instruction [F (1, 12) = 4.108, $P<0.05$] was significant. The simple effect showed that negative images were more negative than the neutral ones under F instructions [F (1, 12) = 5.731, $P<0.05$]. In addition, a significant three-way interaction was observed among the instructions, subsequent response category, and anterior–posterior caudality [F (1.258, 10.896) = 4.626, $P<0.05$]. The follow-up analysis showed that the F instructions provoked a larger negative ERP than the R ones over the frontal scalp region when the subsequent response is miss [F (1, 12) = 7.014, $P<0.05$] (left side, Fig. 4).

In the 300–400 ms window, the main effect was observed in the subsequent response category [F (1, 12) = 31.873, $P<0.001$] and anterior–posterior caudality [F (1.266, 15.188) = 49.199, $P<0.001$]. Furthermore, interaction between instruction and anterior–posterior caudality [F (1.093, 13.102) = 15.540, $P<0.001$] was found. The simple effect analysis showed that the amplitude of the ERP provoked by the R instructions were positive over the posterior scalp region [F (1, 12) = 21.336, $P<0.001$]. In addition, the interaction of the valence and instruction was also significant [F (1, 12) = 5.208, $P<0.05$]. The simple effect showed that the neutral images were more positive than the negative images under R conditions [F (1, 12) = 6.114, $P<0.05$]. Finally, interaction among anterior–posterior caudality, instruction, and subsequent response category occurred [F (1.282, 15.382) = 11.873, $P<0.05$]. The follow-up analysis showed that the amplitude of the ERP provoked by the R instructions appeared more positive than the F ones over the posterior scalp region when the subsequent response is hit [F (1, 12) = 8.451, $P<0.05$] (right side, Fig. 4). There was no other main or interaction effect during this time period.

3. Discussion

In this directed forgetting study, the item method directed forgetting paradigm was used to explore the behavioral and

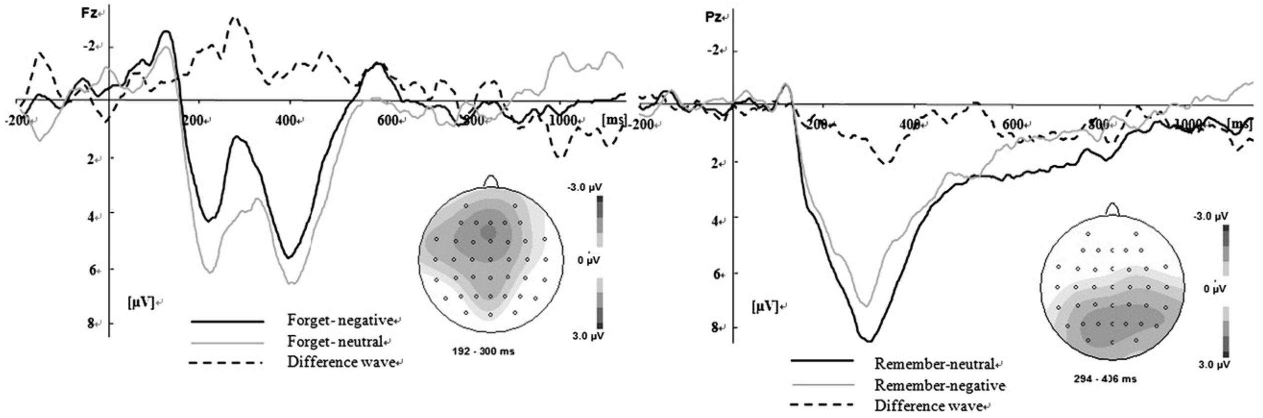

Fig. 3 – Left: grand average ERPs for F instructions and the difference wave (negative-neutral) at Fz. The topographical maps showed the voltage amplitudes of the difference. Right: Grand average ERPs of R instructions and the difference wave (neutral-negative) at Pz. The topographical maps showed the voltage amplitudes of the difference.

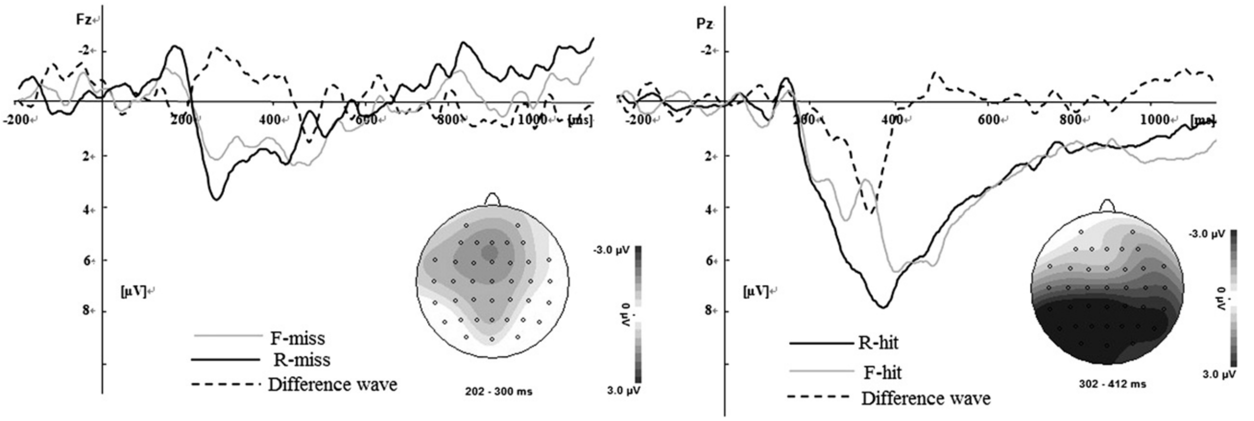

Fig. 4 – ERP waveforms elicited by different instructions were averaged on the basis of subsequent recognition performance. Hit: the study images preceding the instructions were subsequently correctly identified. Miss: the study images preceding the instructions were subsequently incorrectly rejected. Topographical maps of voltage amplitudes showed the difference waveform during the 200–300 ms and 300–400 ms. Left: (F-miss-R-miss), Right: (R-hit–F-hit).

neural mechanisms of neutral and negative images presented in a mixed order. The behavioral results showed that directed forgetting effect occurred for both neutral and negative images. These were in line with those previous directed forgetting studies that also showed directed forgetting effects for emotional information (Depue et al., 2006; Depue et al., 2007; Dumont, 2000; McNally et al., 1999; Tolin et al., 2002). Electrophysiologically, three effects were found related to the current study. The negative images elicited enhanced LPPs compared with the neutral images during image presentation. This was consistent with that obtained by Hauswald et al. (2010). Moreover, the ERPs elicited by the F and R instructions exhibited significant differences in the time windows of 200–300 and 300–400 ms after instruction onset. In addition, there was an interaction between valence and instruction. The implications of these findings are discussed in the succeeding sections.

3.1. *ERPs elicited by the study items*

The negative images elicited enhanced LPPs compared with the neutral images, a result consistent with those of previous studies (Hajcak et al., 2006, 2009; Hamann, 2001). Enhanced LPPs for emotionally negative stimuli indicate enhanced automatic attention allocation to the encoding of the emotional stimuli. Because of this preferential processing, memory for emotional information is enhanced (Hamann, 2001). The present behavioral results, however, showed that the hit rate of the negative images was higher than that of neutral images, while the result for discrimination accuracy was indifferent. This finding is supported by other evidence suggesting that larger LPPs associated with emotional images are more strongly linked to higher hit rates than to increased discrimination accuracy (Hajcak et al., 2006; Hajcak et al., 2009). In the present experiment, participants exhibited a higher hit rate for the negative images than for the neutral images because of their biased recognition of negative images. Other studies also suggest that negative stimuli show biased recognition (Hauswald et al., 2010; Nowicka et al., 2011; Windmann and Kutas, 2001). Although preferential processing of negative images was observed, as represented by enhanced LPPs, directed forgetting continued to occur for the negative images. These results are consistent with other evidence showing that negative information can be intentionally forgotten

(Depue et al., 2006, 2007; Nowicka et al., 2011). The results of the current work, however, differ from those of Hauswald et al. (2010), who suggest that negative images are exempted from directed forgetting. Although the paradigm of both experiments was the same, the stimulus materials used were different. The negative and neutral images that we used did not differ in their arousal levels, whereas in the study of Hauswald et al. they did. Previous studies on memory suppression suggest that negative words and pictures that matched neutral items in terms of arousal can be successfully suppressed (Depue et al., 2006; Johansson et al., 2007). We obtained the same conclusion on directed forgetting in the current work. On the basis of our results and those of Hauswald et al. (2010), we conclude that the arousal of emotional images plays an important role in eliminating intentional forgetting.

3.2. *ERPs elicited by the forget instructions*

The ERPs following F instructions were more negative-going than those associated with the R instructions over the frontal scalp regions in the 200–300 ms time window after instruction onset. On the basis of the grand average waveforms and time interval, we considered the N270 (200–300 ms) a possible secondary ERP component similar to N2. In general, N2 is a marker of a general control process that operates in a go/no-go paradigm (Donkers and van Boxtel, 2004; Eimer, 1993). Comparing the N270 in this study to the N2 in go/no-go paradigms is useful because certain evidence shows that similar inhibition processes are engaged in memory control and the go/no-go task (Hourihan and Taylor, 2006; Levy and Anderson, 2008; Mecklinger et al., 2009; Taylor and Ivanoff, 2003). Hourihan and Taylor (2006) suggest that intentional forgetting may engage cognitive control processes at overt encoding that is analogous to that required to prevent the execution of prepotent overt response. In an ERP study, Mecklinger et al. (2009) found that no-think trials elicited an N2 ERP component that showed a similar centro-parietal scalp distribution as did the successful stopping in a motor stopping experiment in which a stop signal task was used. In accordance with attentional inhibition theory, directed forgetting has been described as resulting from the attentional inhibition of information during encoding (Zacks et al., 1996). Zacks et al. (1996) suggest that participants are previously encouraged to commit words to memory, and F instructions serve to countermand this default covert action by activating attentional control mechanisms. Mechanisms engaged in attentional inhibition are likely associated with cognitive control processes akin to those used to control overt actions (Levy and Anderson, 2008). In recent years, many fMRI studies have also suggest that frontal cognitive control processes play an important part in memory control (Anderson et al., 2004; Levy and Anderson, 2008; Nowicka et al., 2011; Wylie et al., 2008). In the present study, ERPs associated with successful implementation of forget instructions (TBF-miss) elicited a larger negative ERP amplitudes than the unintentional forgotten items (TBR-miss) over the frontal region during the time window of 200–300 ms. The result are in line with the previous evidence and reveal that a frontal inhibition mechanism are engaged in actively stop processes associated with memory formation in the intentional forgetting. Thus, it is reasonable to suggest that the N270 may reflect the active inhibitory control processes of TBF items.

A more important and interesting finding was that F instructions following negative images elicited a larger N270 than those succeeding the neutral instructions over the frontal region. N2 is generally identified as the index of inhibitory control, and the amplitude of N2 reflects the amount of cognitive resources used in control processes (Azizian and Polich, 2007; Donkers and van Boxtel, 2004; Eimer, 1993; Proverbio et al., 2009). Proverbio et al. (2009) found that a no-go related N2 component were larger to irrelevant stimuli that are difficult to suppress in the go/no-go paradigm. The authors interpreted the larger N2 as pointing to more cognitive resources required in difficult suppression tasks. In the present study, participants were encouraged to commit images to memory, and the F instructions served to countermand this default covert action. Thereafter, participants were required to devote more cognitive resources to inhibit this covert action because of the pre-instruction preferential processing of the negative images. Nowicka et al. (2011) found that forgetting emotional information was much more difficult and required considerable effort in an fMRI study. The results of the response time analysis also favored this conclusion. The TBF images showed longer RTs than did the TBR images only under the negative conditions. This result reinforces the inhibition hypothesis: negative TBF images require more time than do neutral images to be recognized because the former are previously more strongly inhibited than neutral ones. Taken together, the larger N270 of the F instructions for emotionally negative images suggests that participants must use more cognitive resources to inhibit the covert action of committing negative images to memory. Thus, although preferential processing of negative images represented by an enhanced LPP was observed, a directed forgetting effect still occurred.

3.3. *ERPs elicited by the remember instructions*

R instructions were more positive-going than the F instructions in the 300–400 ms time window. The largest amplitude was observed over the posterior scale at 360 ms after instruction onset. This positive-going effect associated with the R instructions has been reported in previous studies (Hauswald et al., 2010; Paller, 1990; Paz-Caballero and Menor, 1999; Paz-Caballero et al., 2004). Researches explained the P3-like effect that the R instructions rendered the study items in short-term memory relevant to the encoding task and led to the deployment of attention resources to the study items. In the present study, a broadly distributed P3 component was observed over the posterior scale region. The P3 observed here is a P3b component, which has been linked with attention allocation and memory encoding (Azizian and Polich, 2007). The amplitude of P3 is believed proportional to the amount of attentional resources engaged in processing a given stimulus (Donchin and Coles, 1988). In the current work, when the instruction was R, the participants employed attention to encode the indicated items. The positivity of responses to the R instructions was also associated with successful memorization of the corresponding images, which in turn reflected better recognition of the TBR images. Thus, that the P3 effect reflects the encoding process of TBR items is a reasonable conclusion to draw. In addition, ERPs associated with successful implementation of remember instructions (TBR-hit) elicited larger positive ERP amplitudes than the unintentionally remembered items (TBF-hit) over the posterior region. The results indicate that the successful encoding of the TBR and TBF items involved different mechanisms. In conjunction with the former explanations, we suggest that this posterior wave reflect rehearsal and memory consolidation process.

The ERP results also showed that the R instructions succeeding the neutral images evoked a larger P3 component than did those that succeeding the negative images. Previous studies suggest that P3 amplitude reflects the amount of attentional resources employed for a given task. The P3 amplitude is proportional to the amount of attentional resources engaged in processing a given stimulus (Donchin and Coles, 1988). Evidence indicates an increase in P3 amplitude as task difficulty increases, suggesting that the larger the processing demands needed to keep object information in working memory, the larger the P3 activity (Kusak et al., 2000). Moreover, many studies reveal that remembering neutral items is more difficult than recalling emotional materials (Hamann, 2001). In the present study, participants paid attention to these TBR items and engaged in more elaborate encoding when the R instructions were given. Negative images, however, were already encoded preferentially (larger LPP) before the instructions were provided. By contrast, encoding neutral images necessitated more cognitive resources compared with encoding the negative images. On the basis of previous studies and the present experimental conditions, we propose that the larger P3 component elicited by the R instructions succeeding the neutral images reflects that participants must devote more cognitive resources to further encode neutral images.

3.4. *Conclusion*

In conclusion, this study compared the behavioral performance and neural mechanism of the directed forgetting of neutral and emotionally negative images. Two ERP components were found related to the directed forgetting effect. Firstly, F instructions elicited a larger N2 than did R instructions and successful implementation of the F instructions (TBF-miss) appeared more negative over the frontal region compared with unintentional forgetting (TBR-miss). Secondly, R instructions elicited a larger P3 than did F instructions and successful implementation of the remember instructions (TBR–hit) appeared more positive than the unintentional remembering (TBF-hit) over the posterior scalp region. The former effect suggests that F instructions trigger a frontal mechanism to inhibit the processing of previously presented images. By contrast, the latter reflects that rehearsal and memory consolidation process was elicited by the remember instructions. Moreover, though the negative images were processed preferentially, as indicated by the enhanced LPP, they can still be directed forgotten because of the stronger cognitive inhibitory control exerted on them, as indicated by the enhanced N2.

4. Experimental procedures

4.1. *Participants*

Seventeen right-handed undergraduate students (8 females, 9 males; aged 19–24 years; mean age = 22.3 years) of the Southwest University in China participated in the experiment as paid volunteers. All the subjects were Chinese native speakers, had normal or corrected-to-normal vision, and reported no current or past neurological or psychiatric disease. All subjects signed an informed consent form before participation on the experiment. The experiment was approved by the Academic Committee of the School of Psychology, Southwest University in China.

4.2. *Materials*

The experimental materials consisted of a set of 560 complex images (280 neutral and 280 negative). All of these images were from the Chinese Affective Picture System (CAPS Lu et al., 2005). The two-category materials differed in valence (mean: negative = 2.21 ± 1.01, neutral = 5.46 ± 0.79; F (1, 278) = 266.19, $P < 0.001$), but equaled in terms of arousal (mean: negative = 5.21 ± 1.01, neutral = 4.96 ± 0.79; F (1, 278) = 2.03, $P > 0.05$). These materials were divided into two sets, with each set containing 280 images. One of the sets served as the study items, while the other served as the distractions in the recognition task. Both the study items and distractions matched in terms of valence and arousal. Images from the different valence categories (neutral, negative) had identical sizes and resolutions (15 cm × 10 cm, 100 pixels per inch). In addition, the luminance level was matched across the two-category conditions, and the contrast of the monitor was set to a constant value across all the subjects.

4.3. *Procedures*

The subjects were seated in a quiet room at approximately 150 cm away from a computer screen with the horizontal and vertical visual angles below 6°. They were instructed to avoid blinking or moving their eyes, and to keep their eyes fixed on the monitor rather than look down at their fingers during task performance.

The experiment was divided into two parts: the study and test phases (Fig. 5). A calculation task served as a distraction between these two parts. The study phase comprised 280 trials, with each trial lasting 4800 ms initiated by a 500 ms presentation of a small black cross on the white computer screen. This was followed by the presentation of a blank screen at a duration randomly varied between 200 and 400 ms. After a random blank screen, an image was displayed for 1000 ms. Then, the second fixation "☆" was shown for 1200 ms, followed by another random blank screen. Subsequently, a second fixation was shown: either a "记" (denotes R) as a cue to remember the previous image or a "忘" (denotes F) as cue to forget the previous image. This fixation was shown for another 1500 ms. The order of experimental trials was pseudo-random with the constraint of no more than three consecutive trials with the same type of instruction appearing in sequence. Every two sequential images differed in terms of valence (i.e., neutral-negative and negative-neutral). The subjects were instructed to memorize only the images followed by the R instruction and forget those that followed the F instruction. After 140 trials, the participants went on a short break (20 s), during which they were told to relax. After the break, another 140 images were presented. After the learning phase, the participants performed the calculation test as a distracter task.

In the second part of the experiment (test phase), each trial began with a fixation point (a small black cross) presented for about 500 ms, followed by a random blank screen lasting from

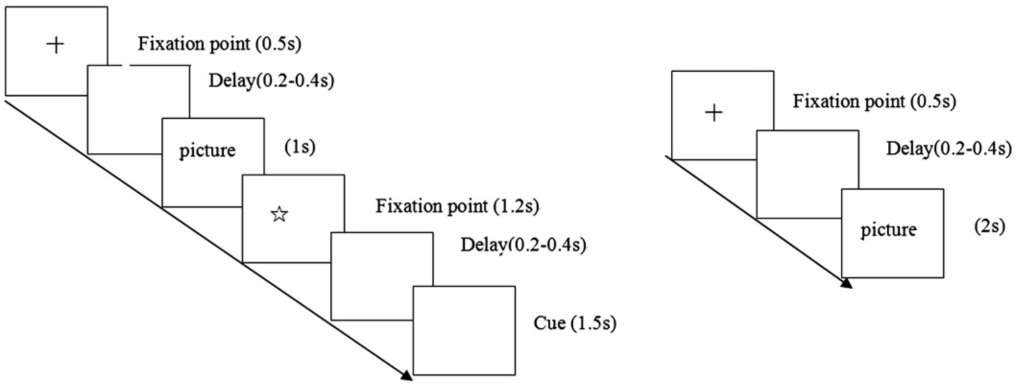

Fig. 5 – Time course of a trial. The left side shows a trial of the study phase and the right side, a trial of the test phase.

200 to 400 ms. Then, both the images presented in the first part and newly presented images were displayed for 2000 ms. Hereafter, the next trial was initiated, adding up to a total of 560 experimental trials, with each trial lasting 2800 ms. The task of the subjects was to decide (within 2800 ms from stimulus onset) whether the image was newly presented or had been shown during the first part of the experiment regardless of the R/F instruction. The subjects were asked to press one of two buttons on the keyboard with the index or middle finger of the right hand to indicate their decisions. The finger assignment to the buttons was balanced across the participants. The participants were instructed to react as quickly and accurately as possible. Again, the order of the stimuli presentation was pseudorandom with the constraint of no more than three consecutive trials with TBF/TBR stimuli and studied/unstudied stimuli.

4.4. *ERP recording and analysis*

Brain electrical activity was recorded from 64 scalp sites using tin electrodes mounted on an elastic cap (Brain Products GmbH, Stockdorfer, Munich, Germany). All channels were referenced to a channel located between Fz and FCz. They were also re-referenced offline to represent recording with respect to linked mastoids. The vertical electrooculogram (EOG) was recorded with electrodes placed above and below the left eye, while the horizontal EOG was recorded with electrodes placed on the right side of the right eye and on the left side of the left eye. Inter-electrode impedance was maintained below 5 kΩ. The electroencephalogram (EEG) and EOG were amplified using a 0.05–100 Hz band pass, and continuously sampled at 500 Hz/channel for offline analysis. Eye movement artifacts (blinks and eye movements) were rejected offline. Trials with EOG artifacts (mean EOG voltage exceeding ± 80 μV) and those contaminated with artifacts because of amplifier clipping, bursts of electromyography activity, or peak-to-peak deflection exceeding ± 80 μV were excluded from averaging.

The averaged epoch for the ERP elicited by the images was 1200 ms, including 1000 ms post-stimulus and 200 ms prestimulus. According to the grand averaged waveforms (Fig. 1), the ERPs elicited by the neutral and negative images were distinct within the time window of 400–1000 ms after the onset of image presentation. In accordance with previous LPP studies (Hajcak et al., 2006; Moser et al., 2006), a group of electrodes (FCz, Cz, CPz, Pz) were extracted for the statistical analysis of LPPs in response to the emotionally negative images within the time window of 400–1000 ms after the onset of image presentation. The mean trial numbers (range in brackets) of the negative and neutral images were 139.4 (138–140) and 138.9 (136–140), respectively.

To explore the brain activity elicited by the instructions, we sorted the EEG data into four experimental conditions: remember-neutral, remember-negative, forget-neutral, and forget-negative. These conditions were based on the combination of the instruction and valence. The EEG of these four conditions was separately overlapped and averaged. The averaged epoch was 1400 ms, which included a 200 ms prestimulus baseline. The mean trial numbers (range in brackets) of the remember-neutral, remember-negative, forget-neutral, and forget-negative conditions were 62.1 (54–68), 64.7 (61–67), 59.8 (53–64), and 66.9 (65–68), respectively. As observed in the grand waveforms and topographical maps, the ERPs elicited by these four conditions were distinct from each other. All their differences were prominent over the frontal, central, and occipital scalp regions (Fig. 2). Thus, the following nine electrode sites were selected for statistical analyses: Fz, F3, F4, Cz, C3, C4, Pz, P3, and P4. To provide more spatial information, we divided these electrode sites into different locations. Hence, the factors entered into ANOVA were the instructions (two levels: F/R), valence in the images (two levels: neutral/negative), left-right hemisphere (left, medial, right), and anterior–posterior caudality (anterior, central, posterior). The visual inspection of Fig. 2 shows that the waveforms diverged around 200 ms after stimulus onset, suggesting differences in the cue-related data in the N2 (200–300 ms), P3 (300–400 ms), and P540 (500–600 ms) time windows. These time periods were chosen for the analysis. Statistical data were adjusted by the Greenhouse–Geisser epsilon correction whenever assumptions of sphericity in the repeated measures analyses were violated and when the number of factor levels exceeded two.

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