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Can't forget: disruption of the right prefrontal cortex impairs voluntary forgetting in a recognition test

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ABSTRACT

The causal influence of the dorsolateral prefrontal cortex (DLPFC) in voluntary forgetting remains unclear. Here, we employed repetitive transcranial magnetic stimulation (rTMS) over the right DLPFC to temporarily disrupt function of this brain region and examined its influence on an item-method directed forgetting (DF) task with both neutral and negative emotional memories. Participants were assigned to either an active or a sham rTMS group, in which we administered stimulation for 20 min before the DF task. We then examined the explicit and implicit DF effects with an explicit recognition and an implicit word completion test. We found that while participants in the sham group showed the classic DF effects in both explicit and implicit memory tests, temporally disrupting activity of the right DLPFC selectively reduced the DF effect on explicit recognition, but not on implicit word completion test. Our findings provide novel evidence that the right DLPFC plays a causal role in voluntary forgetting and support the direct inhibition account of voluntary memory control. Intriguingly, preserved implicit DF effects in the active stimulation group suggest that unintentional expressions of unwanted memories may be more sensitive to DF and less dependent on the right DLPFC.

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Directed forgetting; voluntary memory control; rTMS; emotional memory; explicit/implicit memory tests

Effective control of unwanted memories can benefit our emotional well-being and cognitive functions (Engen & Anderson, 2018). Specifically, voluntary memory control can operate during either memory encoding or retrieval stages (Anderson & Hanslmayr, 2014). During memory encoding, the inhibitory control system can be engaged to truncate in-depth processing of unwanted information and disrupt further consolidation of these memories (Anderson & Hanslmayr, 2014). In the stage of memory retrieval, inhibitory control can be recruited to suppress the retrieval of unwanted memories to disrupt memory traces that support retention. The directed forgetting (DF) paradigm is widely used to investigate the voluntary control of memory during the encoding stage (Bjork, 1989), in which participants are instructed to remember certain stimuli while forget the other stimuli depending on "remember" or "forget" instructions. The DF effect is evidenced by better memory performance for to-be-remembered (TBR) than to-be-forgotten (TBF) stimuli. Although earlier studies suggested that the TBF materials are forgotten due to a lack of active rehearsal (Basden, Basden, & Gargano, 1993; Bjork, 1989), recent studies provide evidence for an alternative account that forgetting involves active, inhibitory control processes (Fawcett & Taylor, 2008; Rizio & Dennis, 2013; Wylie, Foxe, & Taylor, 2008; for a review, see Anderson & Hanslmayr, 2014). Specifically, research has found robust neural activation in the control neural network (e.g., the fronto-parietal brain regions) when participants are cued to forget previously presented materials; this evidence highlights the active nature of voluntary forgetting (Bastin et al., 2012; Gamboa, Sung, Von, Behrens, & Steinmetz, 2018; Nowicka, Marchewka, Jednoróg, Tacikowski, & Brechmann, 2010; Rizio & Dennis, 2013; Wylie et al., 2008).

The DF research typically employs either item method or list method (Anderson & Hanslmayr, 2014; Basden et al., 1993). In the item method, remember or forget cue is provided following each individual stimulus, while in the list method, two lists (each consisting of several stimuli) are presented, with remember or forget cue provided only following the first list. To date, two studies have investigated the causal effect of either left or right dorsolateral prefrontal cortex (DLPFC) on the list-method DF using repetitive transcranial magnetic stimulation (rTMS) or transcranial direct current stimulation (tDCS) technique (Hanslmayr et al., 2012; Silas & Brandt, 2016).

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However, no studies have examined the brain regions that play a causal role in the item-method DF. Many studies have shown that item- and list-method of DF may tap into different neurocognitive mechanisms (involve different brain regions and show different functional connectivity patterns between brain regions; Hanslmayr et al., 2012; Rizio & Dennis, 2013; Taylor & Hamm, 2018), thus the results obtained in list method cannot be simply generalised to item method. According to previous research, the right middle frontal (i.e., the DLPFC) as well as superior frontal gyri are engaged during the item-method DF tasks (Bastin et al., 2012; Gamboa et al., 2018; Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2008). Moreover, when compared with incidental forgetting, voluntary forgetting was associated with greater activation of the right DLPFC (Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2008), which further highlights the critical role of active inhibitory control in the item-method DF effect. To investigate the causal role of the right DLPFC on memory control in an item-method DF task, we used low frequency (1 Hz) rTMS in the current study. Based on prior neuroimaging evidence, we hypothesised that rTMS-disturbed DLPFC would have an impact on voluntary forgetting of memories. Specifically, inhibiting the right DLPFC would lead to decreased DF effect.

Seeing that people have intrinsic motivation to control unpleasant memories (Anderson & Hanslmayr, 2014; Hu, Bergström, Gagnepain, & Anderson, 2017), we included both neutral and negative emotional materials in the task. Some previous studies showed that negative memories are more difficult to voluntarily forget and forgetting negative material is associated with enhanced prefrontal activation (Hauswald, Schulz, Iordanov, & Kissler, 2011; Nowicka et al., 2010; Payne & Corrigan, 2007; Yang et al., 2012). However, other studies have demonstrated that negative materials can be voluntarily forgotten as well as neutral materials (Barnier et al., 2007; Brandt, Nielsen, & Holmes, 2013; Tolin, Hamlin, & Foa, 2002; Wessel & Merckelbach, 2006). Since the prior evidence is inconsistent, we had no prior expectations on whether the rTMS effect would be stronger for negative than neutral items.

Another purpose of the present study is to examine the effect of voluntary forgetting on implicit memory and its possible neural mechanisms. It has been proposed that voluntary control of unwanted memories could influence their explicit/intended as well as implicit/unintended expressions (Gagnepain, Henson, & Anderson, 2014; Hertel & Hayes, 2015; Hertel, Large, Stuck, & Levy, 2012; Hu, Bergström, Bodenhausen, & Rosenfeld, 2015; Kim & Yi, 2013; for a review, see Hu et al., 2017). However, these studies mostly focused on retrieval suppression employing the think/no-think paradigm, in which memory cues are presented and participants are required to deliberately retrieve or suppress the retrieval of associated memory targets according to the think/no-think instructions (Anderson & Green, 2001). Very few studies have investigated whether memory control during the encoding phase could similarly affect unwanted memory's unintended influences. An early study reported that the DF can influence both explicit and implicit memory task performance (Macleod, 1989). On the contrary, other studies failed to observe the DF behavioural effect in the implicit lexical decision task (Paz-Caballero & Menor, 1999; Van Hooff, Whitaker, & Ford, 2009). To further investigate whether voluntary forgetting can influence the unintended influences of unwanted memories, the current study employed an implicit memory test, i.e., a word completion task, in addition to the explicit old/new recognition test.

With respect to the cognitive mechanisms underlying the implicit DF effect, previous studies have demonstrated that the DLPFC is also critical for implicit learning and memory (Brunoni et al., 2013; Lee, Blumenfeld, & d'Esposito, 2013; Zhu et al., 2015). Moreover, a recent meta-analysis showed that explicit and implicit memory involve common neural regions (including the prefrontal cortex) during encoding but distinct neural regions during retrieval (Kim, 2019). Seeing that the DF effect is mainly produced at the stage of memory encoding rather than retrieval (Taylor & Hamm, 2018), it is reasonable to believe that explicit and implicit DF effect might share some brain regions. Meanwhile, some researchers have proposed that active inhibition is critical for both explicit and implicit DF effects (Macleod, 1989; Van Hooff et al., 2009). To test this hypothesis and explore the possible role of the right DLPFC in active inhibition, we plan to examine whether disrupting the right DLPFC will affect both explicit and implicit DF effect.

Methods

Participants

A total of 51 college students (26 females; mean ± standard deviation = 20.6 ± 1.7 years old) were recruited from Shenzhen University as paid participants. Since there were few studies investigating the TMS effect using item-method DF task, we set the sample size at 50 according to our laboratory routine, i.e., 25 subjects per group. The data of one additional participant in the preliminary experiment (in order to test the programmes) was also included in the analyses, so the final sample size was 51. Participant recruitment was complied with the guidelines for rTMS research and each participant was screened for the exclusion criteria (Wassermann, 1998). Participants were randomly assigned into either an active ($n = 25$) or a sham ($n = 26$) TMS group. None of them had any prior experience with TMS before the experiment. All of them passed the colour blindness test. Since previous studies have showed that individual differences in depressive levels can influence DF performance (Power, Dalgleish, Claudio, Tata, & Kentish, 2000; Wingenfeld, Terfehr, Meyer, Löwe, & Spitzer, 2013; Xie, Jiang, & Zhang, 2018; Yang et al., 2016), we matched participants' depression scores between the active and sham stimulation groups using the Chinese versions of the Beck Depression Inventory Second Edition (BDI-II, Beck, Steer, Ball, & Ranieri, 1996). There was no significant difference between the two groups with respect to age, gender, handedness, and BDI-II score (Table 1).

Participants were introduced about the equipment used in the experiment and their tasks. Written informed consents were obtained prior to the experiment. The experimental protocol was approved by the Ethics Committee of Shenzhen University.

Experimental design and stimuli

We employed a two (instruction: remember vs. forget) × two (valence: neutral vs. negative) × two (stimulation group: active vs. sham) mixed design, with the first two factors as within-subject factors and the third one as a between-subject factor.

We used nouns and adjectives as materials. Each word consisted of two Chinese characters. A total of 640 words (320 negative and 320 neutral) were selected from the Chinese Affective Words System (Wang, Zhou, & Luo, 2008), with an equal number of words of adjectives and nouns. Each word had been assessed for its familiarity, valence and arousal on a 9-point scale with a large sample of Chinese participants in a previous survey (Wang et al., 2008). Selected negative and neutral words differed significantly in both arousal (negative = 5.01 ± 0.79, neutral = 4.07 ± 0.35; $t(638) = 19.4$, $p < 0.001$) and valence (negative = 3.52 ± 0.75, neutral = 5.76 ± 0.50; $t(638) = -44.4$, $p < 0.001$). No difference was found in the familiarity between negative and neutral words (negative = 5.32 ± 0.59, neutral = 5.33 ± 0.58; $t(638) = -0.17$, $p = 0.868$).

These 640 words were divided into two subsets, with an equal number of words from neutral and negative conditions and from nouns and adjectives. One subset (320 words) was used in the study phase (80 trials per condition) while the whole 640 words were used in the old/new recognition test (i.e., 320 old words presented in the study phase and 320 new words).

Procedure

All participants experienced the following procedures in order: rTMS stimulation (active or sham control); a direct forgetting task; an implicit memory test and an explicit memory test. We did not counterbalance the order of the implicit and explicit memory tests to avoid unforeseen effects of old/new recognition task on implicit word completion task. Specifically, completing an old/new recognition task first will re-expose participants with all learnt materials, therefore influencing its succeeding word completion task.

The rTMS stimulation. We employed a transcranial magnetic stimulator (Power Mag, Mag & More GmbH, Munich, Germany) with a figure-of-eight coil (double wings of 70-mm diameter). The location of the device was based on a standard EEG cap with the International 10/20 system (Klem, Lüders, Jasper, & Elger, 1999). Individual resting motor threshold (rMT) was measured at the motor cortex (the C4 site on the EEG cap). In particular, we used an ascending staircase method to change the intensity from 30% machine output and fine-tune the stimulation position until 5 out of 5 pulses can result in thumb movements. Then the intensity was decreased in 1% steps until 5 out of 10 pulses can reliably induce thumb movements. The number of TMS pulses applied during rMT estimation varied across participants due to individual differences (range = 25–50, mean = 35). The stimulation intensity was adjusted to allow 50% of the pulses reliably producing thumb movements (Schutter & Van Honk, 2006). This study used an off-line TMS scheme to prevent participants from being affected by device noises during the task. The rTMS was applied in 1 Hz at 100% of the rMT on the right DLPFC (the F4 site on the EEG cap; BA10; see also Borckardt, Reeves, & George, 2009; Herwig, Satrapi, & Schönfeldtlecuona, 2003; Iseger, Padberg, Kenemans, Gevirtz, & Arns, 2017; Penolazzi, Stramaccia, Braga, Mondini, & Galfano, 2014; Silas & Brandt, 2016) for 20 min (1200 pulses). The TMS protocol was coincident with the TMS safety guidelines (Rossi, Hallett, Rossini, & Pascual-Leone, 2009; Wassermann, 1998). For individuals in the active stimulation group, the coil was placed tangentially on the scalp so that the maximal magnetic line of force could go through the F4 site. The average intensity was 42.4% (range from 36% to 52%) of maximal machine output. For participants in the sham stimulation group, the coil was placed at a 45° angle to the head so very limited magnetic line of force could reach the brain (Balconi & Ferrari, 2013; Kimbrell et al., 1999). Before receiving TMS, participants were told that they could end the experiment at any time if they feel pain or uncomfortable during the stimulation phase. Post-stimulation subjective reports from participants revealed that they experienced mild and tolerable discomfort (23/25 in the active group and 0/26 in the sham group). None of the participants terminated the experiment because of uncomfortable sensations induced by TMS stimulation. The simulated electric field is illustrated on an adult brain model in Figure 1 (SimNIBS software, www.simnibs.org; Thielscher, Antunes, & Saturnino, 2015).

Table 1. Demographic data of the active and sham stimulation groups.

Characteristics	Active group ($n = 25$)	Sham group ($n = 26$)	Statistics
Mean age, y	21.0 ± 1.8	20.3 ± 1.6	$t(49) = 1.56$, $p = 0.826$
Gender, male/female	13/12	12/14	
Handedness, right/left	25/0	26/0	
BDI-II	11.3 ± 6.6	9.0 ± 5.5	$t(49) = 1.35$, $p = 0.240$

Note: Descriptive data are presented as mean ± standard deviation. BDI-II, beck depression inventory second edition.

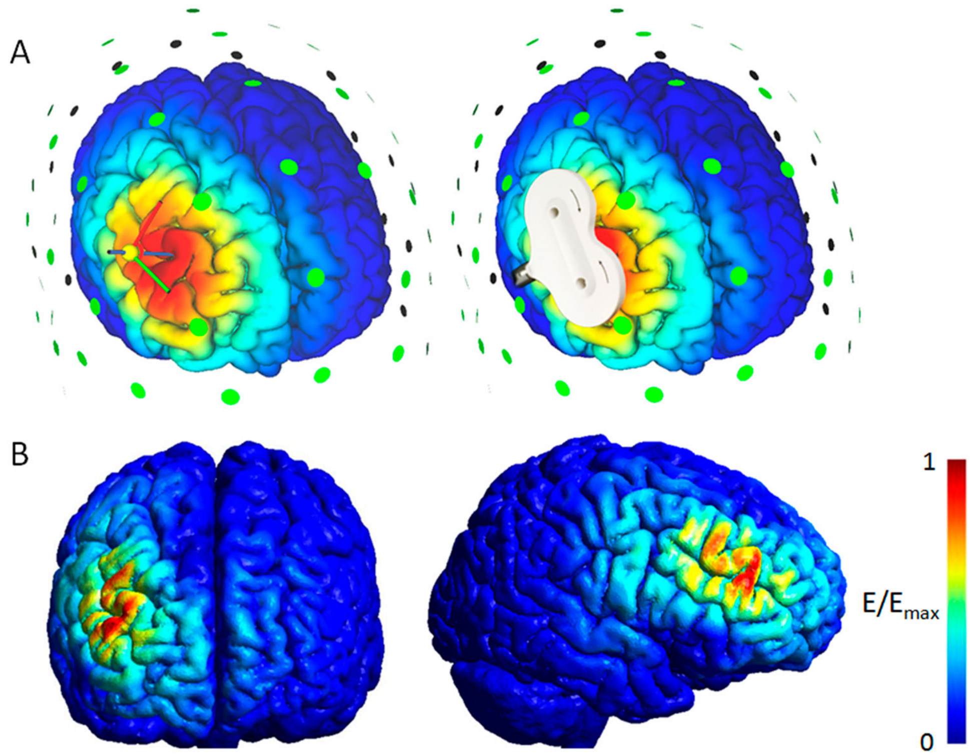

Figure 1. An illustration of the TMS electric field using the SimNIBS. A, the stimulation site and preview of the magnetic vector potential on the brain grey matter surface. The rTMS stimulation was delivered by a figure-of-eight coil at the F4 site. B, simulated electric field for the rTMS figure-of-eight coil. Colour represents the electric field strength scaled from 0 (blue) to the individual maximum (red). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Direct forgetting task

In the study phase, 320 words were randomly presented, and each word was presented only once. The word was presented for 1 s followed by a 3-s long instruction cue. The cue was either a green or a red asterisk, instructing participants to forget or to remember the previously presented word (forget vs. remember = 50% vs. 50%). The assignment of colours to "forget" and "remember" instructions was counterbalanced across participants.[1] Each trial began with a 200 ms fixation and ended with a 1 s blank screen. This study phase was equally divided into four blocks with 80 words in each block, which was separated by self-paced breaks. This phase takes about 30 min.

Implicit memory test

After the study phase, word completion test was conducted immediately to examine voluntary forgetting's impact on implicit memory task performance. This test included 100 words that were randomly selected from the 320 words of the study phase (with 25 words from each of the four within-subject conditions), with each word's first character being printed on a paper. Participants were instructed to write down the word with the first option that came to their mind. Participants were given 5 min for this task and were told to complete the task as quickly as possible. In order to prevent participants from deliberately recalling words from the study phase, they were told that this word completion task was a word filling game unrelated to the previous memory task, and their performance in this game had no impact on their final payment. In Chinese, there are numbers of words with the same initials, so filling out the words which had been presented in the study phase can be regarded as an implicit memory effect.

Explicit memory test

After the word completion task, participants took a 3-min break and then proceeded to an old/new recognition task, in which the 320 studied words were mixed with 320 new words. Seeing that the emotional valence of materials may affect participants' performance on the DF task by affecting the memory of TBR and TBF items respectively (Hauswald et al., 2011; Nowicka et al., 2010; Yang et al., 2012) and that shifting between materials with different emotional valence can incur switching costs (Johnson, 2009; Piguet et al., 2013; Reeck & Egner, 2014), we divided the words into four blocks (negative TBR, negative TBF, neutral TBR and neutral TBF) to avoid the possible interference of such switching processes. In each block, 80 old words and 80 new words (i.e., fillers) were randomly presented and each word was presented only once. Each trial begins with the presentation of a word and participants were required to indicate whether the word was presented in the study phase (old) or not (new) as soon as possible (within 2 s), irrespective of the "forget/remember" instructions. Each trial ended with a 1s blank screen. Blocks were presented in a random sequence and were separated by self-paced breaks. Two different experimenters were responsible for the TMS procedure and later behavioural tasks. The experimenter in charge of giving instructions during DF task and memory tests did not know whether the participant received real or sham stimulation.

Statistics

Statistical analysis was performed using SPSS Statistics 22.0 (IBM, Somers, USA). Descriptive data were presented as mean ± standard errors, unless otherwise mentioned. The significance level was set at 0.05.

Mixed analyses of variance (ANOVA) was performed on behavioural performances, with instruction (remember vs. forget) and valence of words (negative vs. neutral) as within-subject factors, and stimulation group (active vs. sham) as a between-subject factor. Significant interactions were analysed using simple effects models.

Results

Implicit word completion performance

We measured the performance of implicit memory test using the rate of studied words written by participants in the word completion test (i.e., *word completion rate* hereafter; Figure 2). A mixed ANOVA did not find the three-way interaction ($F(1,49) = 0.29$, $p = 0.594$, $\eta_p^2 = 0.006$), nor any interaction or main effects involving rTMS group variables (*F*s < 1). However, we observed a significant main effect of instruction ($F(1,49) = 146.7$, $p < 0.001$, $\eta_p^2 = 0.750$): participants gave more TBR (39.3 ± 1.6%) than TBF words (22.1 ± 0.9%); and a significant main effect of emotion ($F(1,49) = 77.8$, $p < 0.001$, $\eta_p^2 = 0.614$): participants filled out more negative than neutral words (35.8 ± 1.1% vs. 25.7 ± 1.3%). We also found a significant interaction between instruction and emotion ($F(1,49) = 31.2$, $p < 0.001$, $\eta_p^2 = 0.389$). When focusing on the TBR-minus-TBF DF effect to breakdown this interaction, we found that the DF effect was significantly stronger for negative than for neutral words (23.3 ± 1.8% vs. 11.0 ± 1.8%).

Explicit old/new recognition performance

Because the word completion task always preceded the old/new recognition task, we excluded stimuli presented in the word completion task from the old/new recognition analyses. Here, sensitivity (d') and response bias (c) were calculated using hit rates (Hit) and false alarms (FA): $d' = z(\text{Hit}) - z(\text{FA})$ while $c = -0.5 \times [z(\text{Hit}) + z(\text{FA})]$ (Macmillan & Creelman, 1991). A higher d' indicates more accurate memory discrimination; a higher c indicates more conservative response biases. The hit rate and false alarm in each condition is presented in Table 2.

Regarding memory discrimination d' (Figure 3), we first found a main effect of instruction ($F(1,49) = 80.4$, $p < 0.001$, $\eta_p^2 = 0.621$): participants showed higher sensitivity in recognising TBR items (1.39 ± 0.07) than TBF items (0.86 ± 0.06). More importantly, the group by instruction interaction was significant ($F(1,49) = 4.2$, $p = 0.046$, $\eta_p^2 = 0.079$). Simple effect analysis revealed that participants from the active stimulation group showed enhanced d' for TBF items than the sham group (0.99 ± 0.09 vs. 0.74 ± 0.08 vs, $F(1,49) = 4.34$, $p = 0.043$, $\eta_p^2 = 0.081$), whereas d' for TBR items was comparable in the two groups (1.39 ± 0.10 vs. 1.39 ± 0.11, $F(1,49) = 0.001$, $p = 0.978$, $\eta_p^2 < 0.001$). This interactive effect indicates that disrupting the right DLPFC can reduce the DF effects by interrupting people's ability in

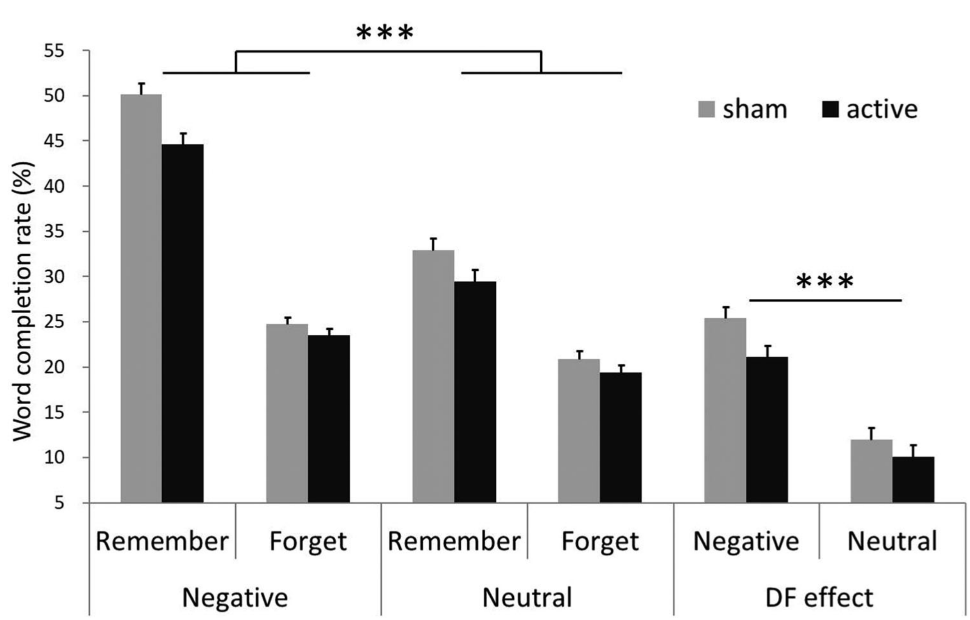

Figure 2. Results of the word completion task. Bars represent standard error of the mean. *** $p < 0.001$.

Table 2. Hit rates and false alarms of the active and sham stimulation groups.

Condition	Active group		Sham group	
	Hit rate	False alarm	Hit rate	False alarm
Negative-remember	0.79 ± 0.11	0.31 ± 0.15	0.76 ± 0.10	0.25 ± 0.14
Negative-forget	0.63 ± 0.16	0.25 ± 0.15	0.44 ± 0.22	0.16 ± 0.12
Neutral-remember	0.77 ± 0.12	0.25 ± 0.16	0.75 ± 0.10	0.24 ± 0.17
Neutral-forget	0.57 ± 0.17	0.24 ± 0.17	0.45 ± 0.23	0.16 ± 0.13

Note: Descriptive data are presented as mean ± standard deviation.

forgetting TBF items rather than the remembering TBR items. When focusing on the TBR-minus-TBF DF effect to break down the interaction, we found that the DF effect was significantly stronger for the sham compared to the active group (0.65 ± 0.08 vs. 0.41 ± 0.08). The three-way interaction was not significant ($F(1,49) = 1.58$, $p = 0.214$, $\eta_p^2 = 0.031$).

With respect to the criterion *c* (Figure 4), we found a significant main effect of instruction ($F(1,49) = 115.8$, $p < 0.001$, $\eta_p^2 = 0.703$): such that participants were more conservative in recognising TBF items than TBR items (0.60 ± 0.07 vs. 0.10 ± 0.05). Furthermore, the main effect of emotion was significant ($F(1,49) = 14.6$, $p < 0.001$, $\eta_p^2 = 0.230$): participants were more conservative in recognising neutral than negative items (0.42 ± 0.06 vs. 0.28 ± 0.05). Intriguingly, we found a significant group effect ($F(1,49) = 10.7$, $p = 0.002$, $\eta_p^2 = 0.179$): such that participants from the active stimulation group became less conservative than the sham stimulation group (0.17 ± 0.08 vs. 0.53 ± 0.08). The interaction between instruction and group was significant ($F(1,49) = 7.36$, $p = 0.009$, $\eta_p^2 = 0.131$). Simple effect analysis showed that active stimulation had a significantly greater impact in reducing *c* for TBF ($F(1,49) = 11.6$, $p = 0.001$, $\eta_p^2 = 0.191$) than for TBR words ($F(1,49) = 6.80$, $p = 0.012$, $\eta_p^2 = 0.122$).

Discussion

Employing rTMS to temporarily disrupt the function of the right DLPFC, the current study examined the causal role of this brain region in voluntary forgetting of neutral and negative emotional memories. We used an item-method DF paradigm to ask people to control unwanted memories and examined the forgetting effect with both explicit and implicit memory tests. It was found that people showed the DF effects in both explicit and implicit memory tests (Macleod, 1989; Van Hooff et al., 2009). Most relevant to the current study, we found that low frequency (1 Hz) rTMS over the right DLPFC reduced participants' ability in forgetting both neutral and negative words in the explicit recognition test, while participants' performance in the implicit word completion task was relatively preserved. By directly manipulating the right DLPFC's activity, our study provided the first evidence that the right DLPFC could have dissociable effects on voluntary forgetting measured by explicit and implicit memory tests.

Disrupting the right DLPFC significantly weakened the DF effect for both negative and neutral memories in an explicit memory test as reflected by the *d′* index. The weakened DF effects were driven by reduced forgetting of TBF words. In contrast, rTMS did not influence the recognition performance of either negative or neutral TBR words. These results provide preliminary evidence that during voluntary forgetting, the right DLPFC is specifically involved in inhibiting unwanted memories but not in selective rehearsal of wanted memories. Meanwhile, the current finding of response bias (*c*) was consistent with previous studies demonstrating response criterion was more conservative for TBF than TBR items (Bastin et al., 2012) and more conservative for neutral than negative items (Bailey & Chapman, 2012). The novel finding is that disrupting the prefrontal cortex can affect the response bias and

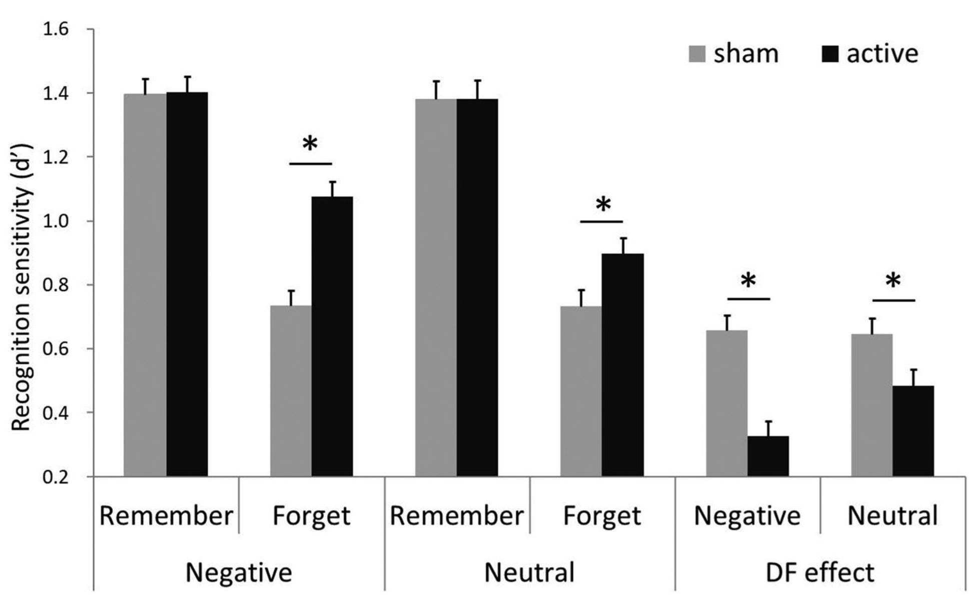

Figure 3. Recognition sensitivity (*d′*) of the old/new recognition test. Bars represent ± standard error of the mean. *$p < 0.05$.

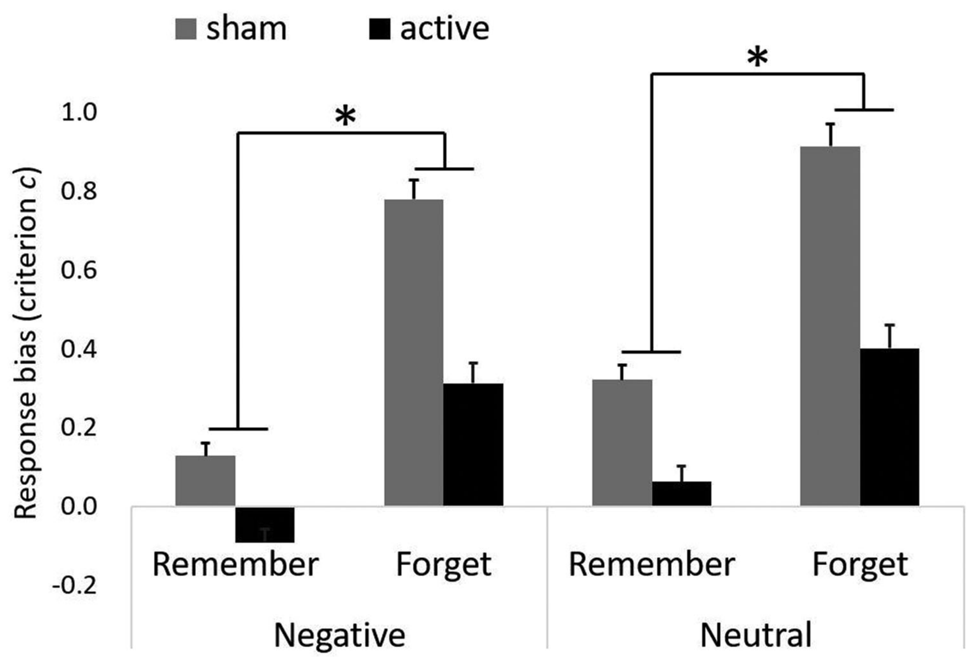

Figure 4. Response bias (criterion c) of the old/new recognition test. Bars represent ± standard error of the mean. *$p < 0.05$.

that the rTMS effect was stronger for TBF than for TBR words. Previous neuroimaging studies employing item-method DF task have found that the efforts to forget TBF items were associated with enhanced activation at the right middle frontal (i.e., the DLPFC) and superior frontal gyri when compared to the remembering of TBR items (Bastin et al., 2012; Gamboa et al., 2018; Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2008). Specifically, increased activity in the right DLPFC during forgetting trials was associated with decreased activity in the left hippocampus, especially during successful voluntary forgetting (Rizio & Dennis, 2013). Together these studies suggest a critical role of active inhibitory control in goal-DF. Unfortunately, this research could not provide neural evidence that directly supports the inhibitory control role of the right DLPFC in regulating other brain regions (such as the hippocampus); future studies are needed to further test the inhibitory control theory of item-method DF.

In addition to the inhibitory control theory, the attentional withdrawal theory is also noteworthy. Although both theories propose that forgetting includes an active processing, the cognitive mechanisms are distinct. By combining the DF task and visual attention paradigm, Taylor (2005) found that participants withdrew attention more quickly from the spatial location previously occupied by TBF items compared to that occupied by TBR items; the finding indicates that attentional orienting might play a role in driving the DF effect, i.e., participants actively withdraw their attention from the TBF items and allocate their cognitive resources on the rehearsal of the TBR items (see also Fawcett & Taylor, 2010; Fawcett, Lawrence, & Taylor, 2016; Lee, 2018; Rubinfeld, Taylor, & Hamm, 2019; Taylor, 2018; Taylor & Fawcett, 2011; Taylor & Hamm, 2018; Thompson & Taylor, 2015; Thompson, Hamm, & Taylor, 2014). Given that the DLPFC is also involved in the attentional control network (for a review, see Brosnan & Wiegand, 2017), disrupting the right DLPFC may also impair the attentional withdrawal processes and influence the memory performance for TBF items. However, the current study found that disrupting the right DLPFC only impaired the forgetting of TBF items without affecting TBR memories. Thus, our results might not support the attentional withdrawal theory account of item-method DF.

We failed to observe a weaker DF effect for negative than for neutral items, which is inconsistent with previous literature demonstrating that forgetting negative memory is more difficult than forgetting neutral memory (Gamboa et al., 2018; Hauswald et al., 2011; Nowicka et al., 2010; Payne & Corrigan, 2007; Yang et al., 2012). Meanwhile, we did not observe the expected greater impact on the DF effect for negative than for neutral materials caused by rTMS; instead, it was found that disruption of the right DLPFC influenced the voluntary forgetting of negative and neutral memories to the same extent. Note that these results are in line with previous literature demonstrating that negative materials can be voluntarily forgotten as well as neutral materials (Barnier et al., 2007; Brandt et al., 2013; Tolin et al., 2002; Wessel & Merckelbach, 2006). The discrepancy between these studies may be due to individual differences. For instance, many studies have demonstrated that depression impairs the ability of voluntary forgetting in the DF task (Cottencin et al., 2008; Hauswald & Kissler, 2008; Joormann & Tran, 2009; Power et al., 2000; Xie et al., 2018). Particularly, one of our previous studies (which used the same materials as the current study) found that participants with high depressive tendencies ($n = 30$, mean BDI-II score = 19.8) had difficulties in forgetting negative words, whereas participants with low depressive tendencies ($n = 30$, mean BDI-II score = 4.0) could successfully forget negative as well as neutral materials (Xie et al., 2018). Since most of the participants in this study are with low depressive tendency (40 out of 51 participants had a BDI-II score < 13) and the other participants were with mild depressive tendency (BDI-II score ranged from 14 to 19), more importantly, we mixed them together for analyses, the null finding regarding emotional valence which is inconsistent with our previous work (Xie et al., 2018) might be attributed to the inhomogeneity (especially the distribution of depressive level) between the samples.

The second goal of the current study was to examine the role of the right DLPFC in the explicit and implicit DF effects. Consistent with previous DF studies using neutral materials (Macleod, 1989; Van Hooff et al., 2009), our result showed that voluntary control of unwanted memories influenced both explicit and implicit memories. Thus, memory control efforts during the encoding processes can affect both intentional and unintentional memory retrieval (Hu et al., 2017). However, while previous studies argued that both explicit and implicit DF effects were the results of active inhibition (Macleod, 1989; Van Hooff et al., 2009), our results suggest that the explicit DF effect, but maybe not the implicit DF effect, relies on DLPFC-dependent inhibitory processes. In this study, the interaction pattern between instruction and emotional valence of the material was different for the two memory tests. In the explicit old/new recognition test, participants showed comparable DF effect for negative and neutral materials; whereas in the implicit word completion task, stronger DF effect was found for negative than for neutral items. The dissociation of DF effects obtained from the two memory tests suggested that explicit and implicit DF effects may rely on different neurocognitive mechanisms. By demonstrating reduced explicit forgetting performance of TBF items in the active stimulation group, our results support the inhibitory control mechanism of voluntary forgetting particularly in the context of explicit memory retrieval.

In the word completion test, enhanced retrieval of TBR negative, compared to neural, words was observed. One possible explanation is that unintended remembering or selective rehearsal is stronger for negative than neutral items. As far as we know, no study has directly examined how intentional forgetting influences the implicit emotional memories. Therefore, the current study provides the first evidence that voluntary forgetting may have a stronger impact for negative memories when such memories are probed in a less-explicit manner. Furthermore, the rTMS finding also supports the view that explicit and implicit memory performance may be influenced by distinctive neural mechanisms, i.e., while the low-frequency rTMS increased the recognition of TBF words in the explicit recognition test, the same manipulation did not influence the DF effects in the implicit memory test. These results suggest that the DF effect shown in the implicit word completion task may less depend on the right DLPFC. When the explicit and implicit DF effects were compared in the active TMS group, the implicit DF effect was relatively intact while the explicit DF effect was significantly weakened due to the DLPFC inhibition. This result suggests that memory control effect (DF effect) might be more robust for unintentional expressions of unwanted memories, which might be immune from the disruptions in the top-down inhibitory control system. That is to say, unintentional memory expressions may be more susceptible to voluntary forgetting, even when such forgetting failed or weakened at an explicit level due to impaired functions of the frontal cortex. In this context, our study raises possibilities that even when voluntary control of unwanted memories fails, such attempts may still be beneficial as they may weaken unwanted memories as evidenced by implicit forgetting effects. This claim converges with previous behavioural findings that the intentional forgetting efforts do not influence memory in an all-or-nothing fashion; instead, unwanted memories can still be accessible, but the fidelity of them can be largely compromised (Fawcett, Taylor, & Nadel, 2013, 2016).

One limitation of this study is the uncertainty of "implicit" nature of the word completion task. Although we asked participants to complete the words using the first came to their mind without intentional recall, no direct measure was available to ensure participants' compliance with instructions. Nevertheless, relatively low recall rates in this task as well as the observed dissociation patterns between explicit and implicit tests supported the implicit nature of this task. Further research is warranted to extend the current findings using other implicit memory tasks. Another limitation of the current study is that it is unclear whether the differences in subjective feelings caused by rTMS affected the task performance. Since we used a sham-stimulation method as the control group, participants in the active vs. sham groups may felt differently during the stimulation phase (Rossi et al., 2009). Future studies are suggested to employ an alternative control method (e.g., target on a task-irrelevant brain region) and retest the findings of this study. In addition, while the study phase of the DF task lasted for 30 min in this study, participants received rTMS for only 20 min. Thus the impaired DLPFC might be recovered in the later period of the DF task (Robertson, Theoret, & Pascual-Leone, 2003; Rossi et al., 2009), resulting an underestimated effect size of the TMS effect. This may be the reason why we did not observe TMS effects in the implicit memory task. It is therefore suggested that an rTMS protocol with longer stimulation duration should be used in the future.

To conclude, by temporarily inhibiting the activity of the right DLPFC, this study provided novel evidence supporting the causal role of the right DLPFC in forgetting unwanted memories (Hanslmayr et al., 2012; Silas & Brandt, 2016) and preliminarily support the inhibitory control theory of item-method DF (Bastin et al., 2012; Gamboa et al., 2018; Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2008). Moreover, employing both explicit and implicit memory tests, we demonstrated for the first time that the DF effect at an implicit level may less depend on the right DLPFC. Our research further suggests that although voluntary forgetting may fail, the efforts are still beneficial.

Note

1. We examined the effect of colour assignment. No significant main effect or interaction effect was found related to this factor (*F*s <1). Thus, colour assignment did not affect task performances.

Disclosure statement

No potential conflict of interest was reported by the authors.

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