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Original Article

Effects of left ventrolateral prefrontal stimulation on forming and maintaining deep and shallow episodic traces

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The levels-of-processing framework, proposing that deep encoding enhances retention, plays a crucial role in episodic memory research. Neuroimaging evidence highlights that increased activity of the left ventrolateral prefrontal cortex during deep encoding predicts subsequent memory success. However, cognitive mechanisms underlying this region's involvement in establishing and consolidating deep and shallow traces remain unclear. In this preregistered study, we investigated whether repetitive transcranial magnetic stimulation over the left ventrolateral prefrontal cortex versus the vertex differentially modulates the formation and maintenance of deep and shallow traces. Trains of 20 Hz online repetitive transcranial magnetic stimulation were delivered over the left ventrolateral prefrontal cortex or vertex during tasks involving pleasantness (deep) and alphabetical order (shallow) judgments of words. Following encoding, two recognition tests assessed immediate and 24-h delayed recognition of words. Compared to the vertex control, ventrolateral prefrontal stimulation selectively disrupted the formation of episodic memory under deep encoding conditions, evidenced by increased response time at encoding and reduced immediate recognition in the deep but not shallow condition. Notably, forgetting rates across the 24-h delay were similar for disrupted deep, intact deep, and shallow items, implying that the rate of trace decay is independent of the strength of trace formation. The constant trace decay indicates that distinct mechanisms are involved in establishing and maintaining episodic traces.

Key words: episodic memory; levels of processing; prefrontal cortex; recognition; rTMS.

Introduction

Episodic memory comprises experiences that are tied to their specific spatial, temporal, and/or source details (Tulving 2002). The processes engaged when encoding such experiences profoundly influence how well they are remembered. This interplay between encoding and retrieval is conceptualized by the levels-of-processing (LOP) framework (Craik and Lockhart 1972). This proposes that deep processing of information, with a greater semantic or associative involvement, leads to superior retention performance compared with shallow (e.g. perceptual or phonological) encoding of the same information, evidenced by a substantial number of behavioral studies (Craik and Tulving 1975; Eysenck 1975; Epstein and Phillips 1976; Moscovitch and Craik 1976; Fisher and Craik 1977; Marks 1991; Royet et al. 2004; Kheirzadeh and Pakzadian 2016; Baddeley and Hitch 2017). This mnemonic advantage from deep encoding in verbal episodic memory is associated with increased activation of the left ventrolateral prefrontal cortex (VLPFC) (Kapur et al. 1994; Wagner et al. 1998; Baker et al. 2001; Otten 2001; Devlin et al. 2003; Fletcher et al. 2003; Köhler et al. 2004), a critical region for semantic processing (Hoffman et al. 2010; Lambon Ralph et al. 2017; Chiou et al. 2018). VLPFC activity at encoding is higher for items later remembered than for those later forgotten, suggesting a critical role in memory formation (Kim 2011).

Neuroimaging data suggest that the VLPFC may contribute disproportionately to memory formation under deep processing conditions. We used repetitive transcranial magnetic stimulation (rTMS), to test this hypothesis, by modulating neural processes during encoding. TMS is a noninvasive technique that temporarily and reversibly alters neural excitability over a focal cortical region. Modulating the neural excitability of the left VLPFC should affect memory performance more severely following deep than shallow processing. However, existing TMS investigations have not observed this differential effect. For instance, Galli et al. (2017) applied 20 Hz online rTMS to left VLPFC and dorsolateral PFC at varying poststimulus intervals during deep (animacy judgment) and shallow (alphabetical judgment) word encoding tasks. There was a detrimental effect on recognition performance when VLPFC rTMS was applied at word offset and 100 ms after offset, whereas no effects were observed at any time point following DLPFC stimulation. However, the disruptive effect of VLPFC rTMS was not dependent upon the depth of encoding. Similar null TMS by LOP task interactions have been found in two other TMS studies

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(Hanslmayr et al. 2014; Vidal-Piñeiro et al. 2014). These previous studies may have lacked the power to detect this effect, either because they included small numbers of participants receiving VLPFC stimulation (12 participants in Vidal-Piñeiro et al. 2014; Galli et al. 2017) or because their design mixed an inhibitory TMS protocol with other stimulation frequencies whose neural effects are less established (Hanslmayr et al. 2014). In contrast, we used an established inhibitory rTMS protocol (20 Hz trains) to perform VLPFC stimulation in 24 participants.

A second aim was to investigate how VLPFC rTMS applied at encoding affects the maintenance of memory traces. Despite clear immediate retention benefits from deep processing, emerging evidence shows that items encoded under deep and shallow processing exhibit similar forgetting characteristics, suggesting that the rate of forgetting is independent of the levels of encoding (Peng et al. 2024a). Other behavioral studies have also found that forgetting rates are unrelated to the strength of initial acquisition, manipulating encoding strength by varying the number of item presentations (Slamecka and McElree 1983; Rivera-Lares et al. 2022) or comparing young with older adults (Rivera-Lares et al. 2023). The present study investigated the rate of forgetting when encoding strength is manipulated at a neural level, by delivering disruptive rTMS during item encoding. It is the first time, to our knowledge, that the longer-term effects of VLPFC rTMS on retention have been assessed.

It is theoretically important to understand whether the left VLPFC selectively modulates the formation of deeply (semantically) encoded items or if it plays a role in episodic traces no matter how they are initially established. The former would resonate with the LOP framework, according to which superior retention following deep processing is a result of broader neural recruitment. Observing differential effects on deep and shallow encoding would shed light on the underlying mechanisms of VLPFC involvement in verbal episodic formation. More importantly, few existing TMS studies have investigated how episodic traces change from immediate to delayed retention following prefrontal cortical stimulation. Accumulated evidence from neuropsychological studies has demonstrated that patients with focal prefrontal lesions exhibit impairments in a range of memory tasks that tax executive control processes (Blumenfeld and Ranganath 2007). However, little is known about the long-term fate of these impaired memories. By using TMS to disturb VLPFC functions, we can assess memory change over time between disrupted and intact memory traces.

To summarize, the present study was designed to address two critical research questions: (i) whether stimulation of left VLPFC versus vertex differentially modulates the formation of deep and shallow episodic traces and (ii) whether rTMS over left VLPFC relative to the vertex differentially affects the maintenance of deeply and shallowly encoded items over a 24-h delay. While measuring recognition performance, almost all relevant TMS studies have relied on either hit rates only or discriminability scores from identical false alarms between deep and shallow tasks (Yeh and Rose 2019). The absence or uniformity of false alarms raises concerns about the reliability of the old/new recognition measure without controlling for response bias (Brady et al. 2023), confounding the possibility that observed changes in recognition induced by the stimulation reflect a shift in response criteria. To avoid this, in the current design items processed at deep and shallow levels were presented in separate blocks during both encoding, immediate and delayed retrieval, enabling separate measurement of hits and false alarms in each condition. Recognition performance was measured using *d* prime and the area under the curve (AUC), taking into account varying response criteria across individuals.

Material and methods

Study design

A repeated-measures study design was employed to contrast memory performance following two LOP tasks with rTMS. Each participant completed two separate stimulation sessions. In each session, participants encoded items under deep and shallow tasks while receiving either VLPFC or vertex rTMS. Recognition for items was tested immediately after encoding and after a 24-h delay. The study procedures and analysis plans were preregistered on the Open Science Framework platform (https://osf.io/5ewhv).

Participants

An a priori power analysis produced a minimum sample of 24 participants to achieve the estimated effect size ($f^2 = 0.56$) from a previous study (Blumenfeld et al. 2014), presuming a 5% significance level (two-sided) and a desired statistical power of 80%. Twenty-five right-handed, native English speakers (19 women), with an average age of 23.28 years (*SD* = 4.10, range = 19 to 32 years), were recruited from our TMS Participant Panel, in which volunteers had previously consented to receive invitations of TMS studies. Prior to taking part in the study, participants underwent screening for any contraindications against rTMS (Wassermann 1998). Informed consent was obtained from all participants in accordance with the protocols approved by the local Research Ethics Committee. One participant was excluded from subsequent analysis due to failure to complete the second stimulation session.

Materials

Stimuli

Three hundred twenty concrete English nouns of 4 to 6 letters in length were selected from the MRC Psycholinguistic database (Wilson 1988). Stimuli were split into two sets of 160 items, used in two stimulation sessions. Each set included 40 stimulated and 40 nonstimulated targets presented at encoding, with the remaining 80 items serving as distractors used in recognition tests. The targets and distractors were matched in word length, concreteness, familiarity, imageability, and frequency according to the SUBTLEX-UK database (van Heuven et al. 2014).

Encoding task

The item encoding task consisted of 80 individual words, presented in two LOP blocks, with each block containing 40 target words. In the deep processing block, participants were instructed to judge whether or not they find the word pleasant (e.g. Pleasant? bear), while, in the shallow block, participants were asked to decide whether or not the two underlined letters were in alphabetical order (e.g. Alphabetical order? knob). Within each block, stimulated and nonstimulated trials were alternated allowing for a safe intertrain interval between stimulation trains (Rossi et al. 2009). Words within blocks were presented in a randomized order.

Retrieval task

To minimize retrieval practice effects on delayed retention, a subset of items was probed at each recognition test to ensure that every presented word was retrieved only once. The immediate test included 40 encoded items, with 20 deep and 20 shallow words, tested in two LOP blocks, each intermixed with 20 distractors. Within each LOP block, stimulated and nonstimulated items were presented separately, along with their respective 10 distractors.

The delayed test contained the remaining 40 encoded items (20 deep and 20 shallow words) and 40 new distractors, administered in the same manner as the immediate test. The stimulation site, stimuli set, and the order of encoding and retrieval blocks were counterbalanced across participants.

Measures

Recognition performance was measured using a forced-choice Old/New test with 4-point confidence ratings. The theoretical discriminability was assessed using *d* prime (z-transformed hit rate minus z-transformed false alarm rate). The larger the *d* prime, the better the theoretical discrimination ability (Wixted 2007). Empirical discriminability was measured through the AUC in the receiver operating characteristic (ROC) analysis derived from confidence ratings. The ROC curve was constructed by plotting the cumulative hit rate against the cumulative false alarm rate for different confidence ratings. The AUC ranges from 0.5 (chance performance) to 1.0 (perfect performance), with higher values indicating better discrimination.

TMS protocol

rTMS was applied using a Magstim rapid magnetic stimulator connected to an eight-shaped coil with an external winding diameter of 70 mm (Magstim Co., Whitland, Dyfed, UK). Motor threshold (MT) was determined by finding the location on the motor cortex that generates maximal contraction in the first dorsal interosseous muscle of the participant's right hand and then finding the minimum level of stimulation that produces a visible contraction on 50% of trials. The intensity of the stimulation was set to 90% of the participant's MT. If the participant's MT could not be evoked or 90% of MT exceeded 60% of the maximum stimulator's power, the stimulation intensity was set to 60%. During encoding, 500 ms trains of 20 Hz online rTMS were delivered beginning 500 ms after the onset of word presentation (Galli et al. 2017).

The left VLPFC was localized using a computerized frameless stereotactic system (Brainsight, Rogue Research Inc.). The participant's head location was coregistered in real time with their previously acquired structural magnetic resonance imaging (MRI) image. Target Montreal Neurological Institute (MNI) coordinates for the left VLPFC were [$x = -50$, $y = 26$, $z = 4$], taken from a previous fMRI study (Fletcher et al. 2003) that used identical encoding tasks as the current study. MNI coordinates were transformed into each participant's native brain space using Statistical Parametric Mapping 12 (SPM12). The vertex, localized using scalp measurement, was used as an active control site since this region is not considered to be involved in memory processes. To ensure head stability during behavioral testing with rTMS, participants rested their heads on a chin rest.

Procedure

The study consisted of two stimulation sessions arranged at least 5 days apart. Each session, involving the encoding task and an immediate recognition test, lasted approximately 30 min. A delayed recognition test was administered online 24 h after each stimulation session (Fig. 1). The encoding task started with the instruction of deep or shallow processing, followed by a black cross on the center of the screen for 500 ms, signaling the appearance of the item. Each word was presented for 2,000 ms, followed by a 500-ms blank screen. Participants were instructed to respond to the word as accurately and quickly as possible by pressing the "Yes" or "No" button on the response box. On simulated trials, 500-ms trains of 20 Hz rTMS were delivered 500 ms after the onset of word presentation. To allow safe intervals between stimulation trains (6 s), stimulation was only delivered in 50% of trials. Stimulated and nonstimulated trials were alternated. After encoding, the immediate recognition test was administered, during which participants responded to each word by pressing "Yes" if it had been encountered in the encoding trials, otherwise pressing "No" on the response box. Following each judgment, there was a 4-point confidence rating with 1 representing "Not sure at all" and 4 indicating "Very sure." No rTMS application was performed at retrieval. Once they completed the immediate retrieval, participants were informed that the second memory test would be delivered online 24 h afterward, following the same manner as the first.

Statistical analysis

Statistical analyses were performed in R (R Core Team 2023), and ROC analysis was run using the ROC Toolbox in Matlab (R2022b, The Mathworks Inc.) (Koen et al. 2017). Main analyses of response times (RTs) and recognition performance adhered to the preregistered analysis plans. Effects of TMS on RTs during encoding tasks were initially examined. The RT model included encoding tasks (LOP: deep vs. shallow) and stimulation sites (site: VLPFC vs. vertex) as fixed effects, with random effects of participants. To control for practice effects across two stimulation sessions and order effects of LOP blocks, two covariates were included in the model: session number (session: first vs. second) and LOP block (block: deep first vs. shallow first). To test how TMS affected immediate and delayed recognition for deeply and shallowly encoded items, mixed-effects models of *d* prime and the AUC included encoding tasks, stimulation sites, and retention intervals (interval: immediate vs. delayed) as fixed effects, with by-participants random effects, controlling for the effects of session number and LOP block. Post hoc pairwise comparisons (Tukey-adjusted *P*-value) were performed to contrast the differences in recognition performance between VLPFC and vertex stimulation under deep or shallow conditions. We report key effects in the main text; full model results with and without item type (stimulated vs. nonstimulated items) are included in Supplementary Materials (Supplementary Tables 1–5).

Results

Response times at encoding

The average RTs for shallow and deep encoding are summarized in Table 1. The mixed-effects model revealed that, overall, the deep task required significantly less processing time than the shallow task ($b = -326.73$, $SE = 32.80$, $P < 0.001$). VLPFC rTMS led to significantly longer response times than vertex stimulation ($b = 64.66$, $SE = 31.07$, $P = 0.039$). This prolonged response time during VLPFC stimulation did not differ between deep and shallow tasks, indicated by a nonsignificant LOP × site interaction ($b = -3.04$, $SE = 41.06$, $P = 0.941$). In addition, participants who completed the shallow task prior to the deep task took significantly longer time than those who started with the deep task first ($b = 250.52$, $SE = 57.62$, $P < 0.001$). This model did not discriminate between stimulated and nonstimulated items. A further model, including item type (stimulated vs. nonstimulated), indicated a marginal site × item type interaction ($b = 68.96$, $SE = 35.22$, $P = 0.052$), showing a tendency for slower RTs during the VLPFC stimulation, as opposed to vertex stimulation, while encoding the stimulated items. Post hoc pairwise comparisons uncovered that, for the stimulated items, the significant difference in RTs between VLPFC and vertex stimulation was found only in the deep

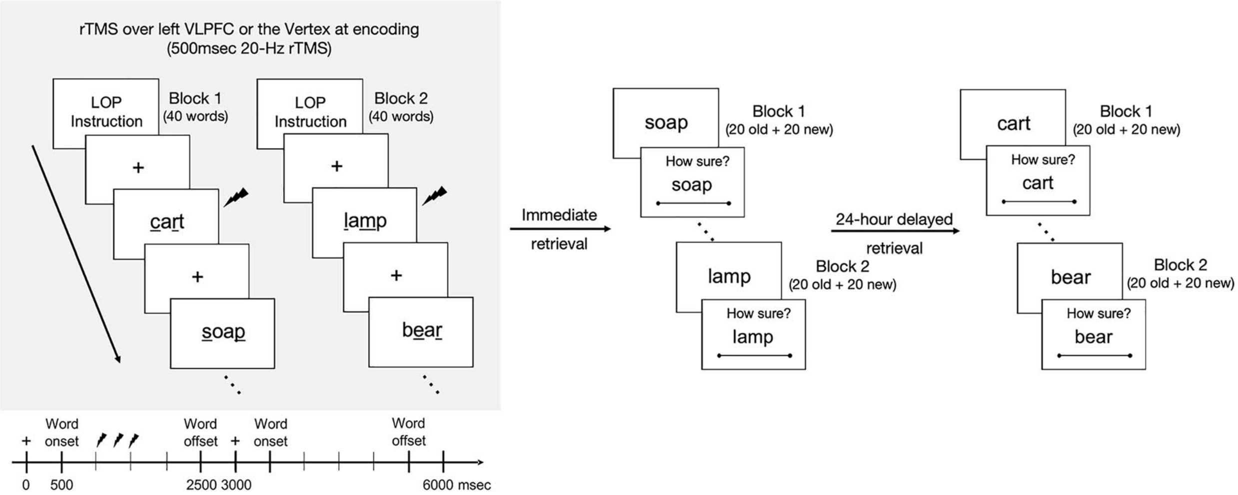

Fig. 1. Schematic procedure of encoding and retrieval tasks.

Table 1. Encoding RTs, *d* prime, and AUC under deep and shallow conditions between VLPFC and vertex stimulation (means and standard errors).

	Encoding/Immediate test		**Delayed test**	
	Deep	**Shallow**	**Deep**	**Shallow**
Encoding RTs (ms)				
VLPFC	1,091 (69)	1,420 (53)		
Vertex	1,026 (57)	1,352 (40)		
d prime				
VLPFC	2.06 (0.14)	0.94 (0.15)	1.10 (0.14)	0.09 (0.11)
Vertex	2.49 (0.12)	0.96 (0.12)	1.37 (0.12)	0.09 (0.10)
AUC				
VLPFC	0.92 (0.01)	0.73 (0.03)	0.81 (0.02)	0.53 (0.02)
Vertex	0.97 (0.01)	0.70 (0.02)	0.84 (0.02)	0.53 (0.02)

(adjusted $P = 0.034$) but not in the shallow condition (adjusted $P = 0.376$). In contrast, for nonstimulated items, no significant results were found between two stimulation sites for deep (adjusted $P > 0.99$) and shallow tasks (adjusted $P = 0.558$). Thus, as expected, VLPFC stimulation affected individuals' ability to make semantic decisions about the words but not orthographic judgments. This effect was restricted to trials when stimulation was delivered (see Supplementary Fig. 1).

Recognition performance

Theoretical discriminability

The average *d* prime for shallow and deep items is summarized in Table 1. The mixed-effects model found that deep processing yielded superior recognition performance to shallow processing ($b = 1.24$, $SE = 0.08$, $P < 0.001$). VLPFC stimulation significantly disrupted the formation of episodic traces ($b = -0.18$, $SE = 0.07$, $P = 0.014$). Critically, this disruption of VLPFC stimulation differentially affected the deep and shallow traces, indicated by a LOP × site interaction ($b = -0.34$, $SE = 0.11$, $P = 0.003$). As shown in Fig. 2, only memory for deep items was poorer in the VLPFC condition compared with vertex. This effect did not interact with item type (see Supplementary Fig. 2). Further post hoc pairwise comparisons confirmed that significant differences in *d* prime at immediate recognition between VLPFC and vertex stimulation were observed in the deep condition (adjusted $P = 0.001$) but not the shallow (adjusted $P = 0.818$).

In terms of episodic memory maintenance, there was a significant drop in performance after 24 h, as indicated by a main effect of retention interval ($b = -0.95$, $SE = 0.06$, $P < 0.001$). More interestingly, neither LOP × interval ($b = -0.19$, $SE = 0.11$, $P = 0.094$) nor LOP × site × interval interactions ($b = 0.14$, $SE = 0.23$, $P = 0.552$) were found. Although VLPFC stimulation interfered with the formation of deep traces, these disrupted traces were not subject to more rapid forgetting over time, as shown by the parallel drop in VLPFC and vertex items (Fig. 3). Consistently, deep and shallow traces also declined in parallel under both VLPFC and vertex conditions, suggesting that the advantage of LOP in recognition did not increase as time elapsed.

Empirical discriminability

When analyzing the AUC, deep processing led to significantly superior recognition performance than shallow ($b = 0.26$, $SE = 0.01$, $P < 0.001$). The performance showed a significant decline from immediate to 24-h delay ($b = -0.16$, $SE = 0.01$, $P < 0.001$), and stimulation over VLPFC induced a differential effect on deep and shallow items, indicated by a significant LOP × site interaction ($b = -0.06$, $SE = 0.02$, $P = 0.005$). Unlike *d* prime, there was a significant LOP × interval interaction ($b = 0.07$, $SE = 0.02$, $P = 0.001$) but no main effect of stimulation site ($b = -0.01$, $SE = 0.01$, $P = 0.377$) (Fig. 4). Post hoc pairwise comparisons supported a significant disturbance of the deep encoding under VLPFC stimulation cf. vertex (adjusted $P = 0.033$) with no such effect for shallow encoding (adjusted $P = 0.111$). Hence, the findings from AUC were in line with *d* prime. There was a differential effect of VLPFC rTMS on recognition performance that was selective for deep but not shallow trace formation. The selective "impairment" of deep traces

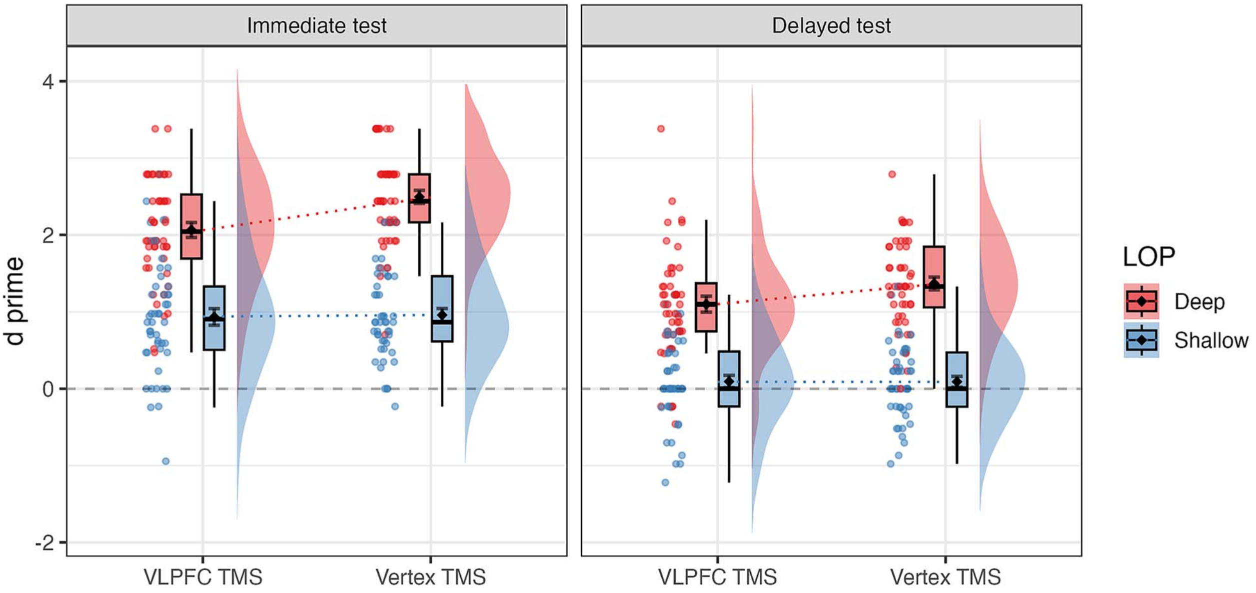

Fig. 2. Recognition performance in *d* prime for deep and shallow processing between VLPFC and vertex stimulation at immediate and delayed tests (means and standard errors are shown on box plots).

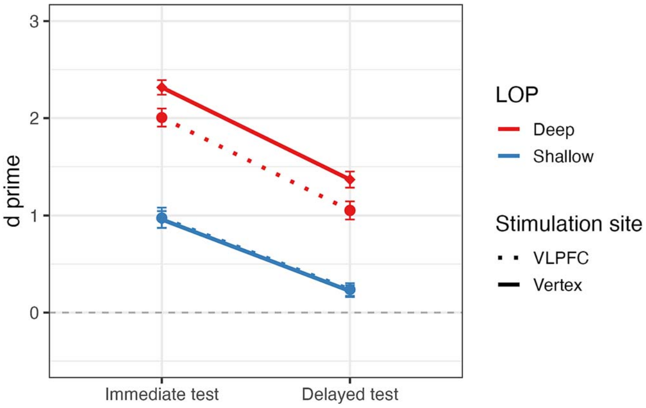

Fig. 3. Performance changes in *d* prime (means and standard errors) for deep and shallow traces following stimulation over the VLPFC and vertex.

induced by left VLPFC stimulation, however, did not differentially affect the maintenance of episodic traces (Fig. 5).

Discussion

The present study investigated whether VLPFC rTMS differentially modulates the formation and maintenance of deep and shallow memory traces. We found a differential effect of stimulation over left VLPFC between deep and shallow processing on RTs at encoding and on recognition discriminability at immediate retrieval. Compared to the vertex control, VLPFC rTMS disrupted the formation of item memory during deep semantic processing, resulting in significantly increased RTs and reduced immediate recognition in this condition only. We also assessed the effect of rTMS on the maintenance of deep and shallow memories for the first time. Interestingly, the results revealed similar memory loss between disrupted and intact deep traces over a 24-h delay, suggesting that the rate of trace decay is not dependent of the strength of trace formation.

The current TMS protocol employed trains of 20 Hz online rTMS over left VLPFC versus the vertex at an intensity below the motor threshold (90%). It produced a net negative effect on episodic memory formation, congruent with the outcomes of a recent meta-analysis (Yeh and Rose 2019). The selective disruption of deep, but not shallow, traces also aligns with previous functional imaging results that highlighted a differential involvement of the left VLPFC in deep and shallow processing (Wagner et al. 1998; Baker et al. 2001; Otten 2001; Devlin et al. 2003; Fletcher et al. 2003; Köhler et al. 2004). Pleasantness judgments involve deeper processing than alphabetic judgments because they necessitate activation of the semantic properties and associations of the target word. This elaborate semantic context is apt to provide more retrieval cues, supporting subsequent retrieval success (Craik 2002). Given the hypothesized function of left VLPFC in controlled semantic processes (Hoffman et al. 2010; Lambon Ralph et al. 2017; Chiou et al. 2018), disruption of this region likely resulted in restricted access to relevant semantic representations, thereby impeding the construction of a rich semantic context for the to-be-remembered item. Indeed, our results suggest that the interference induced by VLPFC rTMS rests on the disturbance of trace elaboration via semantic control rather than an impairment of memory storage or a shift of response criteria during the recognition test. This restricted trace elaboration during deep processing led to a reduction, rather than complete elimination, of the LOP effect at immediate retrieval. It reflects a transient and reversible TMS effect localized to the targeted site, which may not necessarily silence all prefrontal functions. For instance, the involvement of the left DLPFC in short-term or working memory has been reported during memory encoding and retrieval (Osaka et al. 2007; Innocenti et al. 2010; Brunoni and Vanderhasselt 2014). Additionally, it is likely that other cortical regions, such as the posterior parietal cortex, or functional connectivity, contribute to the processes involved in the formation of deep traces (Moscovitch et al. 2016; Yeh and Rose 2019). At the neural level, prefrontal–hippocampal coupling mediated via an oscillatory synchrony mechanism appears to play an essential role in episodic memory formation (Eichenbaum 2017). Through interfering with ongoing neural processing in the left VLPFC, TMS may also disrupt this prefrontal–hippocampal interplay.

The disruptive effect of VLPFC stimulation on deep traces, however, did not further affect trace maintenance, with disrupted

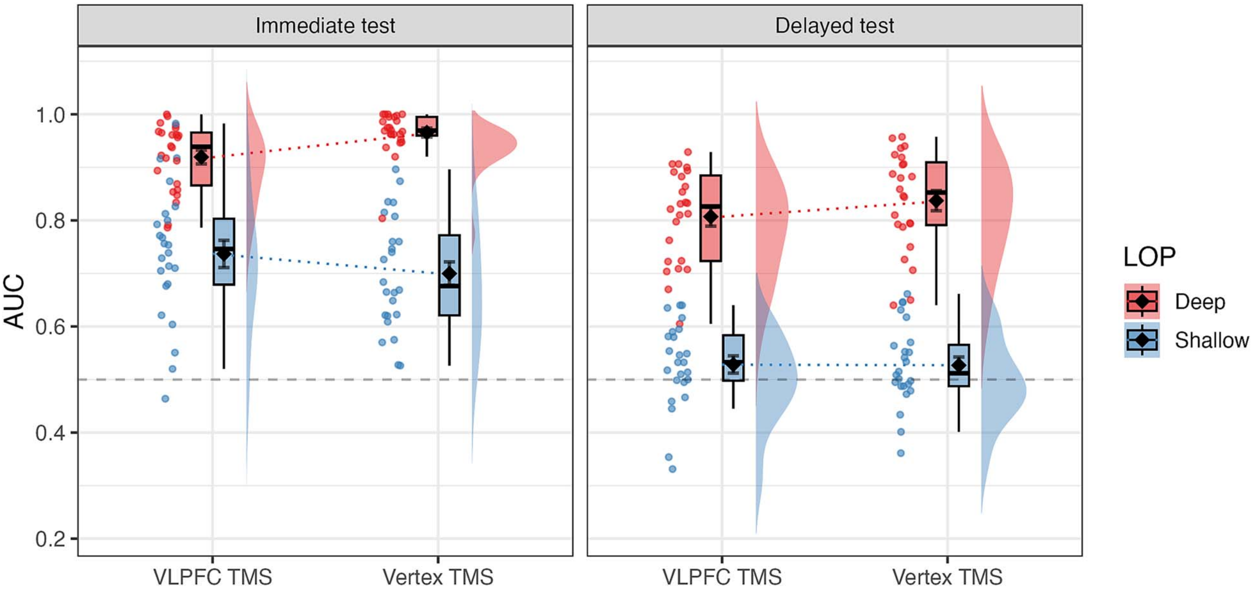

Fig. 4. Recognition performance in AUC for deep and shallow processing between VLPFC and vertex stimulation at immediate and delayed tests (means and standard errors are shown on box plots).

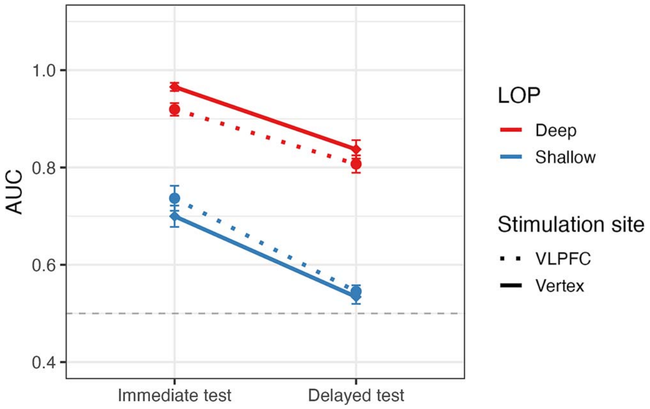

Fig. 5. Performance changes in AUC (means and standard errors) for deep and shallow traces following stimulation over the VLPFC and vertex.

(VLPFC) and intact (vertex) deep traces presenting a parallel decline over a 24-h interval. Parallel changes in memory performance were also observed between deep and shallow traces, collectively suggesting a constant absolute rate of trace decay independent of the processing engaged in trace formation. These findings are in concert with one line of behavioral observations focusing on the relation between the degree of learning and rates of forgetting (Bahrick et al. 1975; Slamecka and McElree 1983; Bahrick 1984; McKenna and Glendon 1985; Meeter et al. 2005; Rivera-Lares et al. 2022; Rivera-Lares et al. 2023; Peng et al. 2024a; Peng et al. 2024b). In these studies, rates of forgetting were compared across varying initial learning performances manipulated during encoding. From the knowledge and skills acquired in educational settings to laboratory materials, including individual words, word pairs, and sentences, the slope of forgetting remains constant and is independent of the initial level of acquisition. Through modulating neural processes at encoding directly, the present study provides an important new source of evidence for this claim. In our study, the same items were encoded in the same way within the same individuals, with rTMS used to manipulate memory strength. Yet we found that these memory traces with varying encoding strengths had similar forgetting characteristics over 24 h.

A possible account lies in an adaptive view of active neuroplasticity in support of processes that function to reverse newly formed episodic traces by altering the state of memory or its contextual cues (Hardt et al. 2013; Nørby 2015; Davis and Zhong 2017; Anderson and Hulbert 2021). This active forgetting allows individuals to maintain greater flexibility and functionality of memory systems, preventing information overload and preparing for new learning. According to consolidation theory, newly encoded episodes remain in a temporary, labile form dependent on the hippocampus and then are transformed into a more stable, long-lasting state distributed in neocortical regions (Dudai 2004; Squire et al. 2015). The circuit architecture of the hippocampus is assumed to be well placed to resist interference via the pattern separation mechanism but is more susceptible to trace decay (Hardt et al. 2013). To free the hippocampus load, this decay-like forgetting, acting as an active and adaptive process, systematically and indiscriminately reverses recently formed traces no matter how they are initially established, more likely during the plastic phases of consolidation when hippocampal traces are prone to modulation (Squire 1992). The parallel retention slopes observed in the present study align with this idea. Although the strength of the initial trace was sometimes disturbed by VLPFC rTMS, the speed of hippocampal trace reversal remained constant, leading to similar rates of forgetting for all memory traces.

Neuropsychological evidence suggests that prefrontal involvement in episodic memory formation reflects top–down processes of cognitive control. The impairments in memory tasks arise as a consequence of deficits in executive control among patients with focal prefrontal lesions. For instance, in contrast to healthy controls, PFC patients exhibit difficulty applying organizational strategies (e.g. semantic clustering) in item recall (Rocchetta and Milner 1993; Gershberg and Shimamura 1995), inhibiting irrelevant or completing memory associations (Shimamura et al. 1995) or tracking the temporal order of episodic events (McAndrews and Milner 1991). However, disrupted deep traces induced by rTMS were not subject to faster forgetting, implying that impaired memories at immediate retrieval, seen in cases of focal PFC lesions, may not necessarily suffer from a rapid rate of forgetting. On the other hand, individuals who exhibit intact immediate memory performance can experience accelerated forgetting over time, a clinical phenomenon named accelerated long-term forgetting, typically found in patients with epilepsy (Butler et al. 2019). Collectively, this implies separate cognitive mechanisms underlying the formation and maintenance of episodic traces.

Our study has extended the TMS investigations from immediate to delayed memory performance. Future studies can build on the current findings. For instance, it would be worthwhile to explore the forgetting characteristics between "impaired" and intact episodic traces using a greater number of time points and longer retention durations, allowing a more detailed analysis of retention curves. These time intervals could span within and beyond the consolidation window to capture a full picture of memory dynamics. Besides, evidence from PFC lesions has indicated differential impairments in performance depending on the type of memory test. In particular, patients demonstrate poorer performance in recall tasks compared to recognition (Dimitrov et al. 1999). However, the majority of existing TMS studies focusing on lateral PFC involvement have measured recognition performance (Yeh and Rose 2019). The present study has addressed issues of response bias in the old/new recognition task, but further exploration of recall tests would provide additional insights into the question. Finally, the role of homologous right VLPFC in encoding and retrieval of episodic events also awaits investigation.

In conclusion, we found a differential effect of VLPFC stimulation on deep and shallow memory encoding. The selective disruption of deep but not shallow items reflects the role of VLPFC in linking items with a wide array of semantic associations and conceptual knowledge. Intriguingly, our results revealed similar characteristics in trace maintenance across disrupted deep, intact deep, and shallow items, implying distinct mechanisms for establishing and maintaining episodic traces.

Author contributions

Nan Peng (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing—original draft, Writing—review & editing), Wei Wu (Investigation, Software, Writing—review & editing), Sergio Della Sala (Conceptualization, Methodology, Supervision, Writing—review & editing), and Paul Hoffman (Conceptualization, Funding acquisition, Methodology, Supervision, Writing—review & editing).

Supplementary material

Supplementary material is available at *Cerebral Cortex* online.

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Conflict of interest statement: None declared.

Data availability

The behavioural data, experimental materials, and analysis code are available in a public repository at https://osf.io/tmg8h/.

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