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Research Article

Transcranial photobiomodulation on the left inferior frontal gyrus enhances Mandarin Chinese L1 and L2 complex sentence processing performances

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ABSTRACT

This study investigated the causal enhancing effect of transcranial photobiomodulation (tPBM) over the left inferior frontal gyrus (LIFG) on syntactically complex Mandarin Chinese first language (L1) and second language (L2) sentence processing performances. Two (L1 and L2) groups of participants (thirty per group) were recruited to receive the double-blind, sham-controlled tPBM intervention via LIFG, followed by the sentence processing, the verbal working memory (WM), and the visual WM tasks. Results revealed a consistent pattern for both groups: (a) tPBM enhanced sentence processing performance but not verbal WM for linear processing of unstructured sequences and visual WM performances; (b) Participants with lower sentence processing performances under sham tPBM benefited more from active tPBM. Taken together, the current study substantiated that tPBM enhanced L1 and L2 sentence processing, and would serve as a promising and cost-effective noninvasive brain stimulation (NIBS) tool for future applications on upregulating the human language faculty.

1. Introduction

The competence in processing sentences especially with complex syntactic structures is a hallmark of human high-level cognition and is viewed as the core of human language faculty (Dehaene et al., 2015; Fitch, 2014; Friederici, 2017; Goucha et al., 2017; Hauser et al., 2002; Nelson et al., 2017). With the development of neurolinguistics, how the brain processes language has been extensively investigated. Several brain regions engage in sentence processing [such as the left inferior frontal gyrus (LIFG; Friederici et al., 2006b; Makuuchi et al., 2009; Meyer et al., 2012; Santi & Grodzinsky, 2010; Xu et al., 2020) and the left posterior temporal cortex (LpTC; Ben-Shachar et al., 2004; Friederici et al., 2009; Goucha & Friederici, 2015; Kinno et al., 2008; Obleser & Kotz, 2010)] and manifest their functional or anatomical plasticity across various kinds of participants [such as healthy participants & patients (Barbier et al., 2019; Ilves et al., 2014; Thompson, 2019; Thompson et al., 2021), young adults & elder adults (Mueller, 2009; Wingfield & Grossman, 2006), adults & children (Davidson, 2010; Müller et al., 1999), first language (L1) speakers & second language (L2) speakers (Davidson & Indefrey, 2009; Proverbio et al., 2002; Steinhauer & Kasparian, 2020; P. Wang et al., 2021, 2022; Wei et al., 2024)].

Considering the significance of sentence processing and for the sake of improving its abilities as well as relieving dysfunctions, intervention towards sentence processing ability has already been followed with

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great interest for decades. Owing to the feasibility of shaping the brain, noninvasive brain stimulation (NIBS), which causes electrophysiological or metabolic effects through physical or chemical approaches to alter brain activities, has become a promising method of modulation towards language ability (Hussey et al., 2015; Minamoto et al., 2014; van der Burght et al., 2023). Not only to patients with language ability deficiency to restore the affected functions (Cotelli et al., 2011; Hartwigsen & Siebner, 2013; Thiel et al., 2013), NIBS is also expected to be applied to healthy adults with continual neural plasticity. Although adults' language network is fully mature in both structure and function, it also appears to remain plastic during the whole lifespan in the course that we continue to learn and process various kinds of language information (either in L1 or L2; Li et al., 2014; Schlegel et al., 2012; Stein et al., 2012; Wang et al., 2021). Moreover, healthy adults with relatively small individual variance compared to patients can serve as an ideal case to explore NIBS's modulatory effects (Hartwigsen et al., 2013; Xin. Qu et al., 2022). Therefore, the investigation of NIBS's effects on L1 and L2 speakers' sentence processing ability holds great significance and is supposed to arouse particular attention.

1.1. The neuromodulation through transcranial photobiomodulation

Drawn on the technique of NIBS, the effect of neuromodulation on language ability has been explored in the past decades mainly using transcranial electrical stimulation (tES) and transcranial magnetic stimulation (TMS) (Cattaneo et al., 2011; Fertonani et al., 2010; Holland et al., 2011). It is worth noting that a large body of tES and TMS studies were interested in the explorations of the causal relationships between the target regions and the behavioral/neural changes in healthy participants by utilizing inhibitory protocols (e.g., Sakreida et al., 2019; Ware et al., 2021; Zhu & Snowman, 2020) while leaving the facilitatory/enhancing effects underspecified. A recent *meta*-analysis also pointed out that the modulation effectiveness of TMS on specific aspects of language ability (e.g., syntactic ability) was relatively limited (Xin. Qu et al., 2022). Therefore, it is necessary to apply an alternative technique with a higher availability of enhancement effect—transcranial photobiomodulation (tPBM)—to upregulate language ability. The tPBM is a newly-developed NIBS technique and can regulate mitochondrial respiration and cellular functions by shining red-to-near-infrared light (600–1100 nm) on the cerebral cortex through the cranium, in a nondestructive and nonthermal optical fashion; specifically, the photochemical reaction within brain cells rests on that complex IV of the mitochondrial respiratory chain is upregulated by absorbing photonic energy to modulate cytochrome *c* oxidase (CCO), which results in the increased oxygen consumption and adenosine triphosphate (ATP) formation (Barrett & Gonzalez-lima, 2013; Eells et al., 2004; Tian et al., 2016; Urquhart et al., 2020; X. Wang et al., 2022; Wong-Riley et al., 2005). Since brain physiology is dependent on oxygenation for energy utilization, tPBM can finally boost brain cognition (Lee et al., 2023; X. Wang et al., 2022; Zhao et al., 2022; see X. Wang et al., 2022 for more detailed information about tPBM functional mechanism).

Recently, tPBM applied on the human forehead has been evidenced to modulate the prefrontal cortex (PFC) by improving the PFC-based cognitive functions in healthy adults (Hwang et al., 2016; Zhao et al., 2022), elderly people (Xiu. Qu et al., 2022), or patients with psychiatric and neurological disorders (Chao et al., 2020; Kerppers et al., 2020; see Lee et al., 2023 for a systematic review). The beneficial effect was found most robustly on PFC-modulated memory ability (Barrett & Gonzalez-lima, 2013; Chan et al., 2021; Holmes et al., 2019; Hwang et al., 2016; Xiu. Qu et al., 2022; Zhao et al., 2022). Barrett and Gonzalez-lima (2013) first conducted a controlled study demonstrating that the performance on a delayed match-to-sample (DMS) memory task was improved for tPBM stimulated group as opposed to the control (placebo) group. Zhao et al. (2022) found that 1064-nm tPBM on the right PFC significantly enhanced the visual working memory (WM) capacities in healthy adults and proposed the mediating effect of electrophysiological activities. In addition, tPBM also produced enhancement for attention, executive functions, and other PFC-based abilities according to recent studies (Blanco et al., 2017; Chan et al., 2019; Moghadam et al., 2017; see also Lee et al., 2023; Salehpour et al., 2019 for systematic review and *meta*-analysis).

1.2. The involvement of the inferior frontal gyrus in syntactically complex sentence processing

LIFG has been proposed to serve as a pivotal engine for sentence processing (Friederici et al., 2003, 2006b, 2017; Jeon, 2014; Hagoort, 2013; Malik-Moraleda et al., 2022; Martins et al., 2019; Vigneau et al., 2006). The sentence structure parsing is proposed to be based on the fundamental operation of *merge*, a process defined by Generative Linguistics to combine two syntactic objects into a larger new constituent (Chomsky, 1995; Friederici, 2017; Miyagawa et al., 2013; Zaccarella & Friederici, 2015). Such a computational ability to build up the syntactic hierarchies is believed to play an essential role in human language faculty, which was found to be largely dependent on the functions of LIFG (e.g., Chen et al., 2021a; Friederici, 2017; Friederici et al., 2006b; Jeon, 2014; Liu et al., 2023; Makuuchi et al., 2009; Meyer et al., 2012; Santi & Grodzinsky, 2010; Zaccarella et al., 2017a; Zaccarella & Friederici, 2015; see also Zaccarella et al., 2017b for the *meta*-analysis on the neurobiology of merge). Zaccarella & Friederici (2015) provided evidence that Brodmann Area (BA) 44, a relatively posterior part of LIFG, roughly corresponding to the inferior frontal operculum, played the primary supporting role for merge when processing syntactic phrases compared to word-list sequences. Meanwhile, the LIFG's engagement was found not only in inflecting languages like German (Zaccarella et al., 2017a) or Dutch (Snijders et al., 2009), but also in Mandarin Chinese and other languages devoid of morphological inflections (Chen et al., 2023a; Wu et al., 2019). For instance, Wu et al. (2019) compared the two-word Chinese phrase consisting of a determiner and a classifier to the two-word list consisting of two classifiers and found that LIFG (esp., BA 44) was significantly engaged in the process of phrase building. These findings evidenced that LIFG's engagement in sentence (esp., syntactic) processing was cross-lingual (Chen et al., 2023a; Wu et al., 2019).

Furthermore, the activation of LIFG directly correlates with the syntactic complexity as shown by the studies focusing on the processing of noncanonical sentences involving word scrambling (Friederici et al., 2006b; Makuuchi et al., 2013), syntactic movement (Caplan et al., 2008; Ben-Shachar et al., 2004; Makuuchi et al., 2013; Santi & Grodzinsky, 2010), and multiple syntactic embeddings (Makuuchi et al., 2009; Wang et al., 2021). Along with natural language, artificial grammar was also exploited to investigate the neural basis of the hierarchical building, through which the semantic confounders could be excluded and all critical variables could be better controlled across the participants (Friederici, 2011; Jeon, 2014; Uddén & Männel, 2018). Similarly, studies with diverse types of artificial grammars also pinpointed that LIFG was working as a combinatorial engine where words were merged together and sentences were built hierarchically (e.g., Bahlmann et al., 2008; Chen et al., 2021a; Friederici et al., 2006a; Liu et al., 2023). In particular, for the first time, Liu et al. (2023) found a significant correlation between the signal intensity of the relatively posterior part of LIFG as identified in their artificial merge grammar processing and the behavioral performances of natural complex sentence processing. These studies, thus, converged on and underlay the critical role of LIFG in merge during complex sentence processing.

It is noteworthy that subregions like BA 45 and BA 47 of LIFG are also involved in sentence processing (Dronkers et al., 2004; Goucha & Friederici, 2015; Musso et al., 2003; Ni et al., 2000; Pallier et al., 2011; Santi & Grodzinsky, 2010; Xiang et al., 2010). For instance, BA 47, roughly the inferior frontal orbitalis, still showed an increase in activation when the size of the jabberwocky (i.e., meaningless) sentence constituent became larger (i.e., syntactically more complex; Pallier et al., 2011). BA

45 was proposed to be inclined to semantic processes, due to the observation that when the derivational affixes conveying meanings were removed from the sentences, its activation became no longer detectable (Goucha & Friederici, 2015). Together with BA 44, these regions constitute the so-called "Broca's complex" (Hagoort, 2005a) which covers the main body of LIFG; therefore, the language function of LIFG beyond single word was generalized to *unification* (Hagoort, 2005b, 2013), predicting and integrating syntactic, semantic, and phonological information in a functionally-gradient fashion (Hagoort & Indefrey, 2014). Since we are particularly interested in the neuromodulating efficacy of tPBM on complex sentence processing, LIFG should serve as an ideal candidate for brain stimulation in this study.

1.3. Hypothesis of tPBM benefits on sentence processing

From the perspective of LIFG's functions in sentence processing, it is of great significance to test whether tPBM on LIFG could exert enhancement on sentence processing performances in the current context of few explorations of tPBM on human language faculty. Nevertheless, it is worth noting that the sentence processing (esp., processing of sentences with complex hierarchical structures) would inevitably recruit verbal WM resources related to linear processing of unstructured sequences (i.e., the sequences without hierarchical structures) to maintain linear verbal components active in memory (Fedorenko et al., 2006; Makuuchi & Friederici, 2013; Meyer et al., 2012) and to rehearse verbal materials (Baddeley, 1986; Baddeley & Hitch, 1974; Fedorenko et al., 2007). Therefore, the verbal WM resources recruited in the sentence processing task might somewhat overlap with that required in the non-sentential verbally-mediated WM task. The correlation between verbal WM span and sentence processing ability was found in both behavioral and neurophysiological evidence (Fiebach et al., 2004; Just & Carpenter, 1992; McDonald, 2006; Vos et al., 2001). Importantly, neuroimaging evidence witnessed the activation of LIFG in some verbally-mediated non-sentential WM tasks such as the item-recognition task and *N*-back task (Smith & Jonides, 1999), suggesting that LIFG might also be responsible for verbal WM for unstructured sequences. Considering the evidence and hypotheses mentioned above, it is unknown yet whether tPBM through LIFG benefits sentence processing *per se* or the boost is somewhat a kind of by-product of the enhancement in terms of verbal WM capacity for unstructured sequences. In order to shed light on this issue, the current study designed a non-sentential verbal WM task additionally (see details in 2.3 & 2.4.2 below) to purify the potential tPBM effects on sentence (i.e., structured sequence) processing.

1.4. A developmental view of tPBM effects on sentence processing

In order to detect the tPBM effect on sentence processing, healthy adults who are native speakers of the target language with relatively small individual variance (compared to L2 learners with higher internal variance considering their differed language background, L2 proficiency level, age of acquisition, etc.) can serve as an ideal case and a starting point for the initial exploration (Hartwigsen et al., 2013; Xin. Qu et al., 2022). Also, evidence showing the large plasticity of L1 (P. Wang et al., 2021, 2022) speakers underlay the feasibility of intervention towards the language ability on them.

Moreover, investigating tPBM effects on sentence processing ability from a language developmental view is also of our primary interest, which could further guide applications of tPBM on groups struggling with language ability deficiency in the near future. Among a wide range of people facing problems with sentence processing, L2 learners who have normal non-language ability (e.g., attention and executive function; compared to patients) enable us to make further investigations, by which the confounding effects brought by the non-language factors could be controlled to a relatively low extent. From recent studies, L2 learners were found to process sentences also with LIFG highly involved, which suggested that L1 and L2 speakers share a common brain area to accomplish sentence processing (e.g., Chen et al., 2019, 2021b; Golestani et al., 2006; Jeon & Frederici, 2013; Mueller et al., 2014; Nakagawa et al., 2022; Nauchi & Sakai, 2009; Sakai et al., 2009; Tao et al., 2021; Umejima et al., 2021; Wartenburger et al., 2003). Specifically, Chen et al. (2019, 2021b) proposed that native Korean speakers showed significant activation in posterior LIFG when reading artificial sentences generated by the Chinese-like grammar based on word category information. Wartenburger et al. (2003) found that the late bilinguals induced greater activation when processing L2 sentences in LIFG than the early ones and even when they processed L1. A recent study on Japanese English learners (Nakagawa et al., 2022) dissociated the brain areas responsible for semantic from syntactic processing and pointed out that LIFG was involved in grammatical encoding in the process of phrase production. Meanwhile, a study of NIBS revealed that L2 learners' ability of syntactic processing showed plasticity and could be enhanced through stimulating LIFG (de Vries et al., 2010). Therefore, it is reasonable to hypothesize that tPBM on LIFG could show enhancing effects on sentence processing for L2 learners as well. Furthermore, when it comes to the hypothesis of the tPBM effect as mentioned in Section 1.3, questions appear pronounced whether L1 speakers and L2 learners would show parallel or divergent patterns of the tPBM effect on complex sentence processing considering differences of verbal WM processes. One may predict that L1 speakers and L2 learners might differ in the effective pattern of tPBM on sentence processing. The WM for L2 elements (i.e., the WM to hold various language information of L2 in mind) is less efficient and its ability is worse than the homolog of L1 speakers, such that the sentence processing in L2 demands WM to a larger extent (Ardila, 2003; McDonald, 2006).

1.5. The present study

This study aimed to explore the tPBM effects on complex sentence processing in both L1 and L2 participants after the stimulation on LIFG. It could be seen from previous studies of tPBM towards cognitive abilities through targeting PFC as a comprehensive entity, focusing on its cognitive abilities such as memory, attention, and executive functions. However, in this study, we departed for investigating the causal effects of tPBM on sentence processing by focusing on the LIFG in the ventral part of the left prefrontal cortex (LPFC), which plays an essential role in sentence processing as aforementioned.

Complex sentences with relative clauses (RC) embedded are challenging even for the L1 healthy adults and were, therefore, used as sentence processing materials in the current study (see also P. Wang et al., 2021, 2022). Meanwhile, to test the aforementioned hypothesis of tPBM effects, a non-sentential verbal WM task was also developed in the present study. Additionally, to test whether tPBM effects on LIFG are domain-specific, a visual WM task, which has already been certified unrelated to LIFG (Zhao et al., 2022), was manipulated as a control task in the current study. By recruiting Mandarin Chinese L1 speakers and L2 learners, the present study investigates the following questions:

(a) Can tPBM on LIFG facilitate sentence processing?
(b) If the answer to question (a) is yes, whether the effect of tPBM applies to sentence processing with the dependence on the verbal WM for unstructured sequences or not?
(c) What is the relationship of effective patterns of tPBM on sentence processing between L1 and L2 groups?

Answers to these questions could be instructive to the utilization of tPBM on the upregulation of sentence processing and provide profound insights into the functional neural plasticity of L1 and L2 sentence processing.

2. Methods

2.1. Participants

Thirty Mandarin Chinese native speakers (14 males, 22.47 ± 1.74 years) and thirty Mandarin Chinese L2 learners whose native languages were Thai or Vietnamese (7 males, 21.97 ± 2.92 years; 6 Thai and 24 Vietnamese) participated in the current study. Thai and Vietnamese are both head-initial languages with postnominal RC locations with regard to the language typology, which mirrors the order of relative clause and head noun in Chinese[3] (Chu, 2020; Liu, 2019; Mao, 2018). Therefore, we recruited these participants from similar language backgrounds under the perspective of complex sentence processing. All Mandarin L2 speakers were overseas students studying in mainland China during the sessions of the experiment, whose Chinese proficiency had reached the intermediate or advanced level with the HSK (i.e., Hanyu Shuiping Kaoshi, a standardized Chinese proficiency test, ranging from bands 1 with low proficiency to 6 with advanced proficiency) band-4 or above passed. All L2 participants completed a questionnaire on language background additionally. They began to learn Chinese as a second language at an average age of 16.25 ± 4.19 years and the mean length of learning was 5.32 ± 3.67 years. They all reported Mandarin Chinese as the second most familiarized language after their mother tongues.

All participants were right-handed, with normal or corrected-to-normal vision and no color blindness or color weakness. None of them reported reading difficulty or any history of psychiatric or neurological diseases. They all signed the consent before the experiment and received a monetary reward afterwards. This study was approved by the Ethics Committee of Beijing Normal University. Data from four participants (two L1 participants and two L2 participants) were excluded because of the relatively lower data quality (i.e., more than 20 % of the trials were missed for not pressing keys on the keyboard) or of the unaccomplishment of the whole experiment. Therefore, twenty-eight L1 participants' (13 males, 22.36 ± 1.73 years) and twenty-eight L2 participants' (6 males, 22.00 ± 2.99 years) data remained as valid and entered subsequent formal analyses.

2.2. Materials

Materials for the sentence processing task, verbal WM task, and visual WM task were prepared respectively. The detailed settings of experimental materials for each task were delineated as follows.

Sentence processing materials. Syntactically complex Chinese sentences containing relative clauses (RC) were adopted for sentence processing task (Fig. 1A). RC is a kind of subordinate clause that modifies a head noun and is embedded within a noun phrase. In Chinese, a language with a head-final RC pattern, a noun phrase containing RC has a structure of "inflection phrase + De (的, complementizer) + head noun". For example, in "支持花花的小孙帮助老张 (literal glosses: support Huahua de Xiaosun know Laozhang; translation: Xiaosun who supports Huahua helps Laozhang)", "支持花花的小孙" is a noun phrase with a RC of "支持花花的". "小孙" is extracted from the clause and leaves a gap. "小孙" is coindexed with the gap and is called the filler because it should fill the gap (Fig. 1A). To comprehend this kind of sentence needs reordering and integration across a long-distance filler-gap dependency, necessary for hierarchical syntactic building. Thus, sentences with RCs involve great complexity of syntactic computation, the processing of which highly involves LIFG (Santi & Grodzinsky, 2010; Xu et al., 2020) and is assumed by the present study to show high potential to be modulated by tPBM on LIFG.

[3] The control of L2 learners' mother tongues aimed to increase the typological differences between Chinese and their L1s so that they could process L2 sentences in a distinctive fashion from L1, which could minish the confounding effect brought by the syntactic similarity.

In order to increase the variation of the materials, a total of 72 complex sentences containing RCs were generated, including 36 sentences with subjective relative clauses (SRC) and 36 sentences with objective relative clauses (ORC) embedded at either subject or object positions of the main clauses. Each sentence consists of six words, and the detailed structure of sentences is illustrated in Fig. 1A. Specifically, 12 two-syllable verbs selected from the HSK-4 vocabulary syllabus and 12 two-syllable common names (i.e., nouns) from HSK textbooks were used to build all complex sentences. Moreover, word frequencies and the frequencies of collocation between two nouns/verbs or a noun and a verb were carefully controlled so that participants were unable to process the sentences or make judgments with any possible strategies unrelated to language processing. Following Xu et al. (2020) and Liu et al. (2023), a probing statement of thematic relation (i.e., the relation of "who did what to whom") was attached to each sentence trial for the correctness judgment to detect participants' performance of syntactic processing (Fig. 1A). The probing sentences were also controlled regarding the collocation frequencies between words and the frequencies of probing verbs concerning their location (i.e., in main clauses or relative clauses), with half being correct/incorrect.

Verbal WM materials. The verbal WM task aimed to detect the verbal WM capacity for unstructured sequences, such that the stimuli in the verbal WM task were generated matching the linear word sequential pattern of sentence processing stimuli (see similar designs in Liu et al., 2023; Wu et al., 2024; Zaccarella et al., 2017a). 6 nouns or 6 verbs were arranged in a linear sequence to form a noun list or a verb list (Fig. 1B). This task shared the same pool of words as the sentence processing task. A total of 36 noun lists and 36 verb lists were generated. The frequencies of word appearance and collocation were also controlled. The probing statement for the word-list trial was like "帮助-5?", which asked participants to judge whether "帮助" appeared at the fifth position of the word list (Fig. 1B). Half of the probing statements were correct/incorrect. The frequencies of questioned words and their locations in the sequence were also balanced.

Visual WM materials. An orientation WM accuracy task was applied to assess the ability of visual working memory by requiring participants to remember the orientations of a set of items. The stimuli of the visual WM task were presented on the screen with a black fixation point surrounded by different number of bars (2° in length and 0.5° in width). All bars were presented within two 4° × 7.3° rectangular regions that were centered 3° to the left and right of the central fixation point (0.4° × 0.4°). The visual WM task consisted of two experimental conditions (load 2 and load 6) and a catch trial condition. For two experimental conditions, one or three bars were placed on each hemifield left or right to the fixation point for load 2 or load 6 condition. The orientation of bars was set at random between 0° and 180° but any two bars on the same screen were at least 20° apart (Fig. 1C).

2.3. tPBM protocol

The 1064-nm tPBM stimulation was conducted using a diode-pumped solid-state laser with a linewidth of ± 1 nm (Model JL-LS-100 developed by Jieliang Medical Device Inc., Jiangxi, China). The 150 mW/cm^2 power density dosage of the laser beam was adopted, with a total area of 13.57 cm^2, resulting in a continuous power output of 2036 mW. The energy emitted by the laser diode at this setting was only 15 % of the Maximum Permissible Exposure (MPE) to the skin (i.e., 1.0 W/cm^2) according to the ANSI Z136.1–2014 standard, with no adverse effects detected from previous studies (X. Wang et al., 2022). The laser device was handheld, and participants were instructed to wear protective eyewear provided by the laser device manufacturer to protect their eyes from laser light. In reference to the standard 10–20 EEG electrode placement system, the stimulation site was centered at F7 (Fig. 2A). According to Koessler et al. (2009), F7 is projected on BA 45 in the cerebral cortex. With a diameter of about 4 cm, the laser beam could roughly cover the main body of LIFG (including BA 44, BA 45, and BA

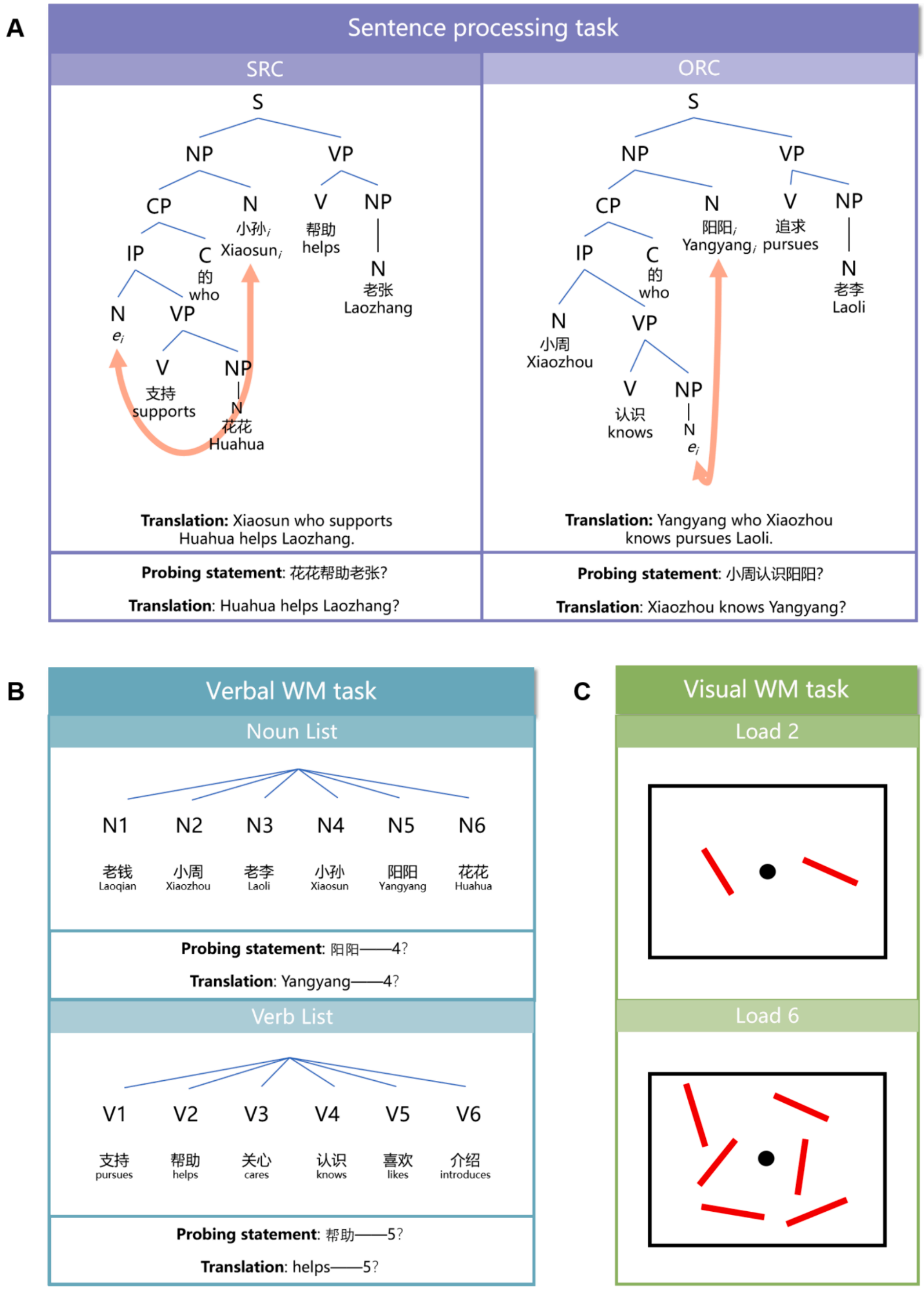

Fig. 1. **(A)** Examples of materials in the sentence processing task. Every sentence contains either an SRC or an ORC with subject or object being extracted and leaving a gap. Sentence structures are presented in the form of a syntactic tree. Every Chinese word is attached to its English literal gloss and the English translation of the whole sentence and probing statement are provided below. The gap (*e*) and the target dependent noun (N) are co-indexed by the subscript "*i*" and linked by an orange arc. S: subject; NP: noun phrase; N: noun; VP: verb phrase; V: verb; CP: complementizer phrase; IP: inflection phrase; C: complementizer; *e*: gap. **(B)** Examples of the noun (name in Chinese) and verb word list in verbal WM task. Each list consists of 6 words in a linear sequence. Each word in the word list is attached with its English literal gloss. The probing statement and its English translation are presented below. **(C)** Examples of materials in visual WM task. A fixation point is surrounded by two and six bars in the condition of load 2 and load 6.

47). Both active and sham tPBM stimulation lasted for 16 min. No laser beam was emitted during sham sessions. The ambient noise (mainly caused by the cooling fan in the machine) was the same for sham or active sessions.

2.4. Procedures

2.4.1. Experimental procedure

The current study adopted a double-blind, sham-controlled tPBM experimental protocol. Specifically, each participant completed two experimental sessions separated by at least seven days to minimize the practice effect. One sham (placebo) stimulation session and one active stimulation session were performed respectively, the order of which was randomized and counterbalanced across participants (Fig. 2B). The purpose and design of the current experiment were covered up towards participants.

At the beginning of each experimental session, participants performed training tasks first to ensure all of them could reach above the chance level of accuracy of all tasks. 16-min tPBM treatment was conducted then, during which participants were required to keep awake and

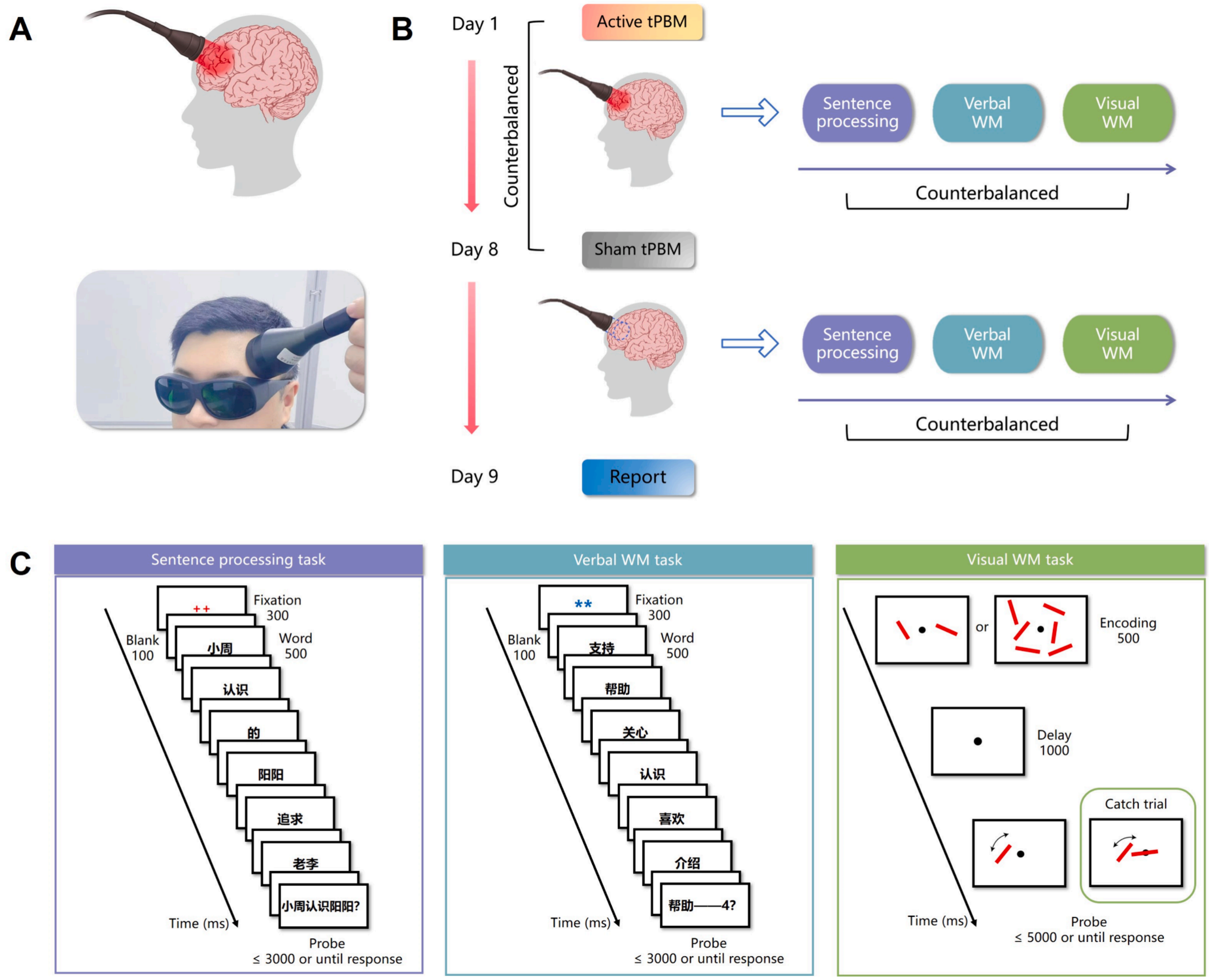

Fig. 2. (**A**) The stimulation site was located on the left inferior frontal gyrus (LIFG) as shown in the diagram (upper) and the picture (lower) on which the 1064-nm tPBM was being applied to a simulated participant. (**B**) The experimental procedure of tPBM stimulation. Two sessions of tPBM were separated by seven days with one active and one sham tPBM session. After 16-min tPBM stimulation, three tasks were accomplished in counterbalanced order. On the 9th day, participants were asked to report or guess in which session they received active tPBM stimulation according to their subjective feelings. **(C)** The procedures of three tasks. Sentence processing task and verbal WM task presented the trials word by word and asked participants to make T/F judgements on the probe screens. In the visual WM task, participants were asked to adjust the rotatable bar to its original position after encoding and delay screens. The catch trial presented a fixed bar across the fixation point and asked participants to turn the rotatable bar parallel to it.

mute. Three tasks, which lasted within 40 min in total, were performed with counterbalanced order across participants immediately after the tPBM treatment. It is of note that, based on previous research which found that tPBM on healthy participants came into effect immediately after the stimulation (Holmes et al., 2019) and the real-time effect lasted at least 45 min (Zhao et al., 2022), our experimental duration fell within the effective time frame of tPBM intervention. All participants reported no feelings or only minor feelings of tPBM treatment. On the day after the second session, participants were required to report or guess which session they thought to be the active stimulation session (Fig. 2B). Results showed that participants guessed below the chance level (hit = 35.72 %; miss = 32.14 %; uncertain = 32.14 %), suggesting that they were not aware of the condition of active or sham tPBM stimulation.

2.4.2. Procedures of tasks

As for the sentence processing task and verbal WM task, stimuli were presented through E-Prime version 3.0 (Psychology Software Tools, Inc., Pittsburgh, PA, USA). Specifically, a fixation point was presented first for 300 ms and followed by a 100-ms blank. Subsequently, complex sentences and word lists were presented word by word, with one word for 500 ms followed by a 100-ms blank. Attached to each sentence or word list, a probing statement was presented in whole sentence and lasted for a maximum of 3 s. Participants were instructed to judge the statement's correctness and to press the corresponding buttons on the keyboard. The screen for probing statements terminated immediately after the participants pressed the button and was followed by a 1000-ms intertrial interval (ITI) (Fig. 2C). A total of 72 complex sentences were presented in a pseudorandom order [i.e., sentences of the same RC type (ORC or SRC) would not appear more than three times consecutively]. Similarly, no more than three noun or verb word-lists would appear consecutively in a pseudorandom order in verbal WM task with 72 word-lists in total.

In the visual WM task, the screen of memory encoding was presented for 500 ms and followed by a 1000-ms blank screen of delay. Next, the probing screen was presented for at most 5 s with a rotatable bar appearing at any position of two or six bars among the encoding arrays. Participants were instructed to adjust the bar with the mouse to the orientation according to their memory of the coded bars and press the left button. For the catch trial condition, a fixed bar with random orientation would lie across on the fixation point with another rotatable bar presented at a random place aside from the fixation point. Participants needed to adjust the orientation of the rotatable bar parallelly to the fixed bar in at most 5 s and press the left button of the mouse (Fig. 2C), after which the probe screen terminated and was followed by a 1000-ms ITI. All screens of visual WM task were presented using Psychtoolbox version 3.0.19 (Kleiner et al., 2007) in Matlab version R2020b (MathWorks Inc., Natick, MA). The whole run of this task consisted of 5 blocks with 240 trials in total (96 of load 2, 96 of load 6, and 48 catch trials in random order).

2.5. Data analyses

The data of accuracy (ACC) and response time (RT) of true/false judgment were directly recorded in the sentence processing task and verbal WM task. As for the visual WM task, the differences between the real orientation of the bar and response orientation and RTs were collected first. To unify the dependent variable calculated from every task, the accuracy data was acquired further. Owing to the setting of 20° apart between any two bars, the response to one trial was classified as correct (i.e., ACC=1) if the difference was between ± 20°.

To avoid accuracy (ACC) − response time (RT) trade-offs, a measure of *overall performance* was used, which weighted the RT with the error rate (ER) according to the formula: $P = RT(1 + 2ER)$, in which ER was equal to "1 – ACC" (Lyons et al., 2014). This measure could be interpreted as an adjusted RT penalized for inaccurate performances, where a higher value indicates worse performance (Lyons et al., 2014). The behavioral changes between sham and active conditions (i.e., the behavioral advantages brought by the tPBM effect) were acquired by the differences of P ($\Delta P = sham - active$) between the two stimulation conditions. The data of each group in the current research was interpolated according to the box plot. Outliers that were beyond $Q1 - 1.5{*}IQR$ or $Q3 + 1.5{*}IQR$ were interpolated by the values of $Q1 - 1.5{*}IQR$ or $Q3 + 1.5{*}IQR$ correspondingly. This method of data cleaning could reduce the effect of extreme values while keeping the data distribution relatively stable.

To certify the global effectiveness of tPBM modulation on the two groups, tests of 2-way mixed-effect repeated-measure analysis of variance (ANOVA) with stimulation condition (sham and active) and group (L1 and L2) as factors were performed on P for each task. Given the common practice of grouping participants depending on high and low cognitive capacities in neuromodulation studies, which usually found that cognitive ability improvement existed mainly or more robustly for individuals with lower original capacity (Hsu et al., 2014; Tseng et al., 2012), the analyses with the same purpose were conducted in the current study in case tPBM showed a significant enhancement. Nevertheless, we did not simply group participants in subgroups of low and high primal capacity because the proportion of orders of tPBM sessions the participants were assigned with (i.e., sham stimulation first or active stimulation first) could be unbalanced in different subgroups. A correlation analysis between initial performance (i.e., P on sham condition) and the change of performance (ΔP) was performed instead, which could certify the correlation if the lower initial performance correlated larger change of performance after tPBM stimulation. It is worth noting that, given that the initial performances between different tasks could be highly correlated, the initial performance and the change of performance in the same task may be correlated with false positives. When testing the numerical relationship between two variables of interest, their correlation results will be misleading if other confounding variables are numerically related to the variables of interest. To rule out this possibility, partial correlations were performed between the initial performance and the change of performance in the same task, with the initial performances in other tasks partially out when significant correlations were detected (see similar practice in Liu et al, 2023). Partial correlation measures the degree of correlation between two variables with the effect of a set of controlling variables removed. Specifically, the partial correlation between X and Y given a set of controlling variables $Z = \{Z_1, Z_2, \ldots, Z_n\}$, written $\rho_{XY \cdot Z}$, is the correlation between the residual e_X and e_Y resulting from the linear regression of X with Z and Y with Z respectively (see more detailed delineation of statistical methods in Cohen et al., 2003).

The statistical tests in the current study were accomplished through JASP version 0.17.2.1 (https://jasp-stats.org/) and R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria; https://www.R-project.org/).

3. Results

3.1. tPBM over LIFG enhanced sentence processing performance in both L1 and L2 participants

For the sentence processing task, the results of 2-way mixed-effect ANOVA (Fig. 3A) showed a significant main effect of stimulation condition [F (1, 54) = 10.931, p = 0.002, η_p^2 = 0.168]. Specifically, compared with the sham tPBM stimulation condition, the performance on the active session was significantly better with a lower P value (sham: 2556.09 ± 733.21 ms; active: 2343.36 ± 674.59 ms), suggesting the increased performances of complex sentence processing both for L1 and L2 group due to tPBM. The follow-up paired sample t test revealed that the active tPBM enhanced sentence processing performance for both L1 [t (27) = 2.085, p = 0.047, Cohen's d = 0.394; sham = 2104.35 ± 442.42 ms, active: 1948.92 ± 395.06 ms] and L2 [t(27) = 2.575, p = 0.016, Cohen's d = 0.487; sham = 3009.46 ± 688.90 ms, active: 2737.80 ± 669.50 ms] groups. In addition, the ANOVA also manifested the strong main effect of group factor [F (1, 54) = 38.592, p < 0.001, η_p^2 = 0.417], such that L1′s performance (2026.63 ± 422.91 ms) was much better than L2 (2873.63 ± 686.88 ms), suggesting the different ability with regard to language proficiency. Moreover, the null result of the interaction effect of ANOVA [F (1, 54) = 0.809, p = 0.372, η_p^2 = 0.015] revealed that L1 and L2 groups showed a similar extent to be enhanced by tPBM.

3.2. tPBM over LIFG failed to enhance working memory performance

Similarly, a 2-way mixed-effect ANOVA was performed with stimulation condition (sham and active) and group (L1 and L2) as factors on the non-sentential verbal WM task (Fig. 3B). However, no stimulation condition main effect [F (1, 54) = 1.835, p = 0.181, η_p^2 = 0.033] or interaction effect [F (1,54) = 0.223, p = 0.639, η_p^2 = 0.004] between group and stimulation condition could be identified. This result suggested that active tPBM on LIFG did not benefit the performance of verbal WM for unstructured sequences as opposed to sentence processing for both L1 and L2 groups. Considering the discrepant coding difficulty toward Chinese words between L1 and L2, the main effect of group was pronounced [F (1, 54) = 12.914, p < 0.001, η_p^2 = 0.193], such that L1 reached better performance (1903.58 ± 371.30 ms) with lower P value when compared to L2 (2312.63 ± 564.48 ms).

As for the visual WM task which was manipulated as a non-language control in the current study, a 2-way mixed-effect ANOVA showed null effects either for group main effect [F(1, 54) = 0.549, p = 0.462, η_p^2 = 0.004], stimulation condition main effect [F (1, 54) = 0.016, p = 0.899, η_p^2 = 0.010], or the interaction between them [F (1, 54) = 0.234, p = 0.631, η_p^2 < 0.001] (Fig. 3C) as expected. The current results revealed the fact that the tPBM stimulation on LPFC exerted little effect on visual WM regardless of the groups of participants. Furthermore, the two groups showed similar performance on the visual WM task in contrast to the two language-related tasks above.

3.3. Inability to process complex sentences predicts large tPBM benefits

To test whether the extent of tPBM boost related to the primal

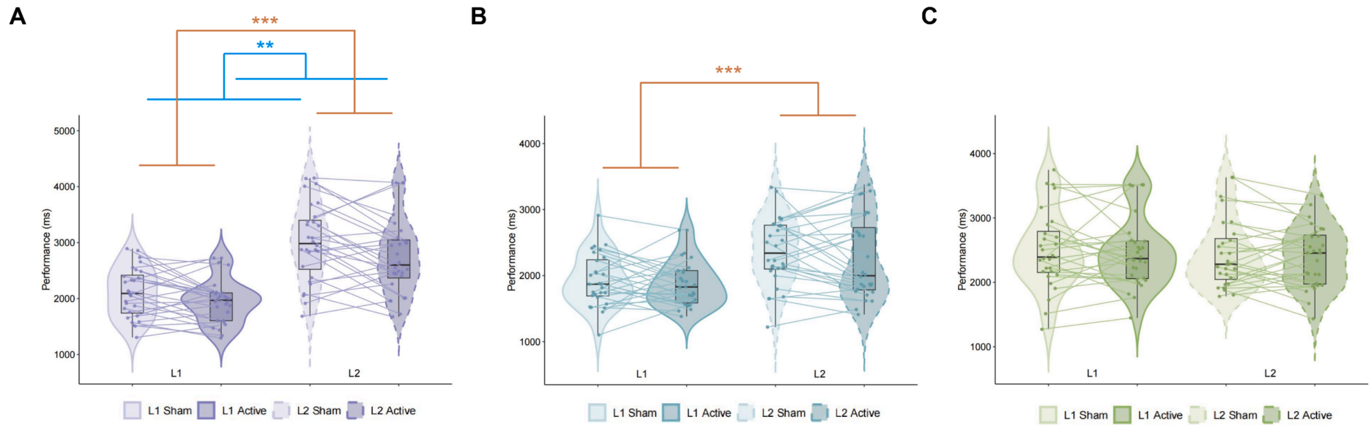

Fig. 3. The violin plots of ANOVA results in (**A**) sentence processing task; (**B**) verbal WM task; (**C**) visual WM task. Each dot refers to one participant. The lines connect the measurements of the same individuals. The line in the box plot represents the median of the data. The violin plots for L1 and L2 are bordered with solid and dashed lines respectively. The plots in lighter color refer to sham condition and the darker ones refer to the active condition. The blue line of significance shows the main effect of stimulation condition and the orange one shows the main effect of group. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

performance in sentence processing task, a correlation task between P on sham condition and ΔP was conducted. Given that the initial performances between the sentence processing task and verbal WM task were correlated in the L1 group (Pearson's correlation $r = 0.395$, $p = 0.038$, Fig. 4A), the Pearson correlation analysis between initial performance (i.e., P on sham condition) and the change of performance (ΔP) was conducted with the initial performance of verbal WM task partially out. As expected, the initial performance on the sentence processing task was positively correlated with the change of performance (sham – active) on the same task for the L1 group (Pearson's correlation $r_{partial} = 0.537$, $p = 0.004$, Fig. 4B).

For the L2 group, the initial performance in the sentence processing task was correlated with that in the verbal WM task (Pearson's correlation $r = 0.718$, $p < 0.001$, Fig. 4C). With initial performance in the verbal WM task partially out, the partial correlation between the initial performance on the sentence processing task and the change of performance (sham – active) on the same task was also significant (Pearson's correlation $r_{partial} = 0.421$, $p = 0.029$, Fig. 4D).

4. Discussion

In the present study, we mainly applied tPBM to L1 and L2 sentence processing task(s) with non-sentential verbal WM task and visual WM task additionally involved, aiming to investigate the tPBM effect on sentence processing and figure out the effective pattern influenced by WM in L1 speakers and L2 learners. Results showed that tPBM on LIFG selectively enhanced sentence processing performances in both L1 and L2 groups. Along with the positive correlation between verbal WM and sentence processing performances under the sham condition, it was revealed that the resources recruited in the sentence processing task did relate to that in the non-sentential verbal WM task, but they did not benefit from tPBM modulation simultaneously. Therefore, current results did not support the dependency on the verbal WM for unstructured sequences in-between the tPBM stimulation and the modulation of sentence processing. In sentence processing task, making judgments on probing statements of thematic role assignment required reordering and integration of sentential elements (Friederici, 2017; Xu et al., 2020), thereby the overall performance (indicator combining the ACC and RT) of sentence processing task could reliably reflect the sentence processing ability. Together, our results supported that tPBM benefited sentence processing ability both for L1 and L2 speakers, which should not be necessarily attributed to the verbal WM capacity for unstructured sequences. The null results of the interaction effect between the group and stimulation type factor validated that L1 and L2 showed similar patterns of modulation. Moreover, the non-significant results of tPBM on WM capacities suggested that tPBM on LIFG was specific to language (esp., complex sentence) processing. Specifically, L1 and L2 differed in language-related tasks (sentence processing task and verbal WM task) but not in the nonverbal task of visual WM, indicating that L1 and L2 matched on nonverbal task so that the parallel pattern of modulation between L1 and L2 was consolidated. In the sentence processing task, we further found that participants with worse initial performance received more enhancement through tPBM such that the inability to process complex sentences can predict large tPBM benefits, which was consistent with the results from prior neuromodulation studies (Hsu et al., 2014; Tseng et al., 2012).

4.1. The enhancing effect of tPBM via LIFG on sentence processing ability

With converging evidence showing that tPBM reveals enhancement towards cognitive abilities such as WM, attention, and executive functions, tPBM has been acknowledged as a promising NIBS technique for neuromodulation (Barrett & Gonzalez-lima, 2013; Blanco et al., 2017; Chan et al., 2019, 2021; Holmes et al., 2019; Hwang et al., 2016; Moghadam et al., 2017; Xiu. Qu et al., 2022; Zhao et al., 2022). The current study extended tPBM's application to the high-level cognitive ability specific to human beings—sentence processing ability by using the sentence processing task in L1 and L2 groups. In the sentence processing task, participants needed to reorder sentential elements in RCs with syntactic movement and then construct hierarchical structures, which cost a high load of syntactic computation (Friederici, 2017; Xu et al., 2020). Combined with our results indicating that the ability of sentence processing could be significantly enhanced, it became a novel complementary finding that in general, the metabolic and hemodynamic changes induced by tPBM on LIFG could also boost one of the highest-level cognitions of human beings—language faculty. Furthermore, our results revealed that tPBM's contribution to sentence processing through simulating LIFG should not be necessarily caused by the increase of the verbal WM capacity for unstructured sequence processing as a by-product. Hence, this study is inclined to support the functionally-specific role of the LIFG on sentence processing.

Nevertheless, it is noteworthy that the selective tPBM enhancement pattern did not deny the contribution of verbal WM capacity to sentence processing as discussed to a large extent in the prior relative studies (Caplan & Waters, 1999; Fedorenko et al., 2006, 2007; Makuuchi et al., 2009; Makuuchi & Friederici, 2013; Meyer et al., 2012; Santi & Grodzinsky, 2007). There was also proposed a verbal WM system specific to syntactic/linguistic processing for structured sequences (i.e., sentences) in the interpretive stage (separated from the verbal WM system recruited by verbally mediated WM task) according to some studies (e.g., Caplan

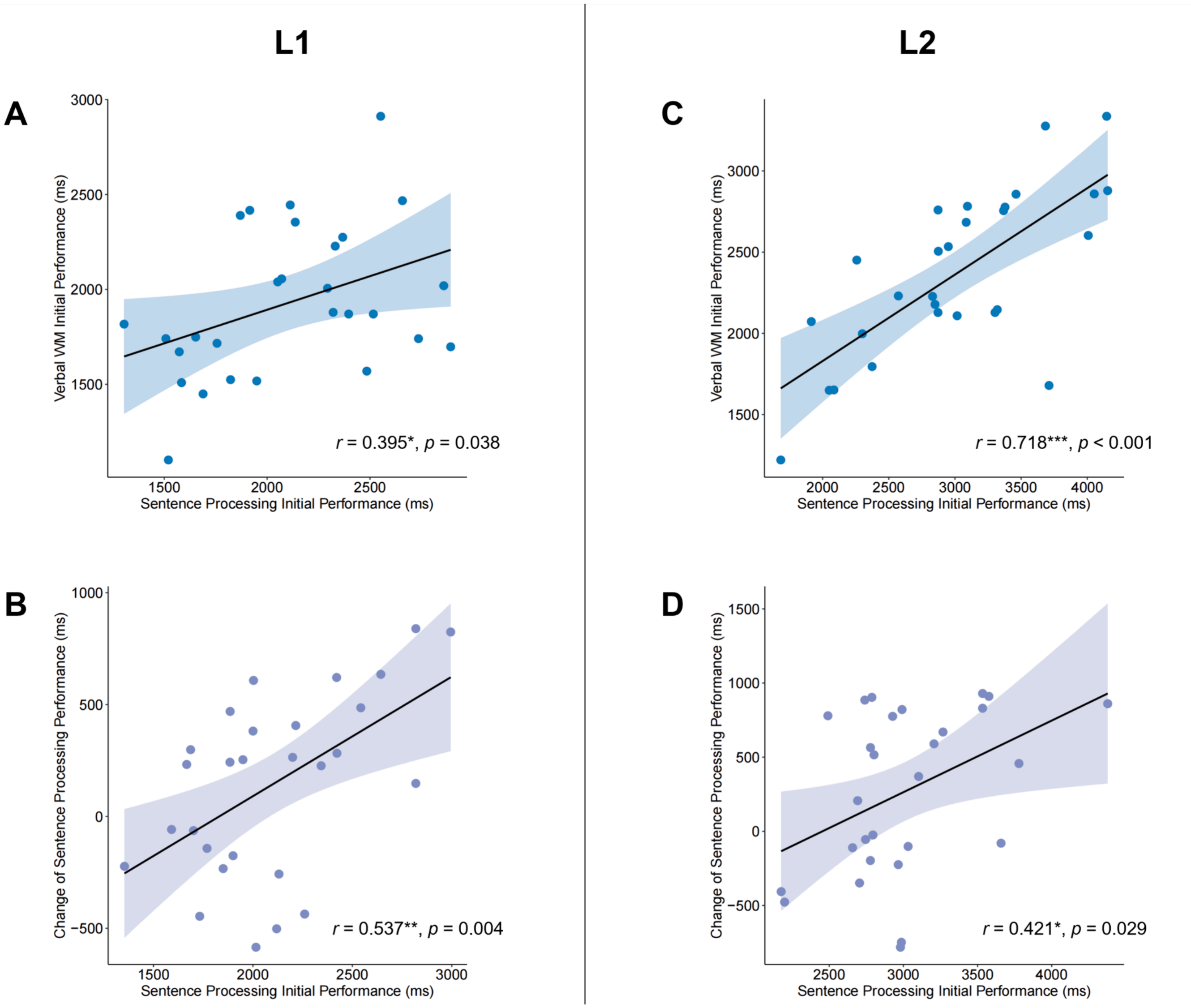

Fig. 4. The correlation between (**A**) Sentence processing initial performance (i.e., *P* on sham condition) & verbal WM initial performance for L1; (**B**) Sentence processing initial performance & change of sentence processing performance (partial) for L1; (**C**) Sentence processing initial performance & verbal WM initial performance for L2; (**D**) Sentence processing initial performance & change of sentence processing performance (partial) for L2. The shaded areas represent 95 % confidence intervals. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

& Waters, 1999; whereas challenged and questioned by Fedorenko et al., 2006, 2007), and such a WM system for structured sequences was further assumed to be independent from the pure hierarchical computation (Makuuchi et al., 2009; Makuuchi & Friederici, 2013). From this dichotomous view of verbal WM system, it was non-exclusionary that the tPBM modulation on sentence processing was mediated by the verbal WM for structured sequences in the interpretive stage inside the sentence processing resources, even though we had ruled out the influence of the verbal WM for unstructured sequences. Therefore, we have to acknowledge that our results have provided little evidence towards this issue due to the fact that we did not separate the verbal WM for structured sequences from sole hierarchical computation inside sentence processing resources. However, we might tap into some potential to explore the influence of the verbal WM for structured sequences on the tPBM effect on sentence processing performances by considering the variance of sentence type with regard to verbal WM loads additionally. In the materials of the sentence processing task, two subtypes of RCs, ORCs and SRCs, were involved. According to the Dependency Locality Theory (DLT) from Gibson (1998), the difference in processing difficulty between ORCs and SRCs is mainly caused by different sentential WM loads in processing dependencies with various linear distances. Specifically, the dependent distance between the filler and the gap is longer in SRC than ORC in Mandarin Chinese (Fig. 1A), accordingly resulting in a preference for ORC in Chinese, which was supported by behavioral (Sung et al., 2016; Xu et al., 2019) and neurological studies (Packard et al., 2010; Xu et al., 2020). A 3-way ANOVA including sentence type factor (ORC and SRC) besides group and stimulation condition was performed in the sentence processing task to justify whether the tPBM effect varied depending on the different sentential memory loads of sentence types. Results showed that neither the 2-way interaction between stimulation condition and sentence type [F (1, 54) < 0.001, $p = 0.990$, $\eta_p^2 < 0.001$] nor the 3-way interaction among stimulation condition, sentence type, and group [F (1, 54) $=$ 0.379, $p = 0.541$, $\eta_p^2 = 0.007$] was significant, therefore suggesting that the tPBM effects on ORC and SRC were parallel in both L1 and L2 groups. The null results of interactions provided additional plausible evidence that tPBM did not enhance sentence processing selectively in terms of WM loads. It might be interpreted that tPBM's positive effects on sentence processing ability were not influenced by the verbal WM capacity for structured sequences inside sentence processing resources.

Nevertheless, it is still premature to draw such a conclusion, considering the possibility that the verbal WM related to structured sequence processing could serve as a mediator, exerting equally substantial enhancing effects on both ORC and SRC sentences due to the fact that both subtypes were highly complex. Syntactically simpler sentences with much lower WM loads might be recruited for comparison in future studies to have the effects of verbal WM for structured sequences scrutinized in a systematic fashion. In a nutshell, the results of the current study could not thoroughly exclude the potential mediating effect of the verbal WM necessary for structured sequences inside complex sentence processing resources.

Moreover, in addition to neuroimaging research which found cerebral activation during cognitive tasks (Liu et al., 2023; Makuuchi et al., 2009; Zaccarella & Friederici, 2015), studies of NIBS could provide us with causal evidence of the relationship between the stimulated brain regions and its cognitive functions (Hartwigsen, 2015), which was seen as the significance of the current study. The causal relationship between LIFG and sentence processing ability was supported by several prior studies (de Vries et al., 2010; Kuhnke et al., 2017; Meyer et al., 2018; Sakai et al., 2002; Uddén et al., 2017; Wu et al., 2024). TMS was adopted by Kuhnke et al. (2017) to suggest the causal involvement of LIFG in reordering during sentence processing. De Vries et al. (2010) found Broca's area (BA 44/45) was causally related to the ability to detect syntactic violations in artificial grammar using transcranial direct current stimulation (tDCS). As a further contribution, our results provided new evidence for a causal role of LIFG for sentence processing, through the positive intervention effect of tPBM for the first time.

4.2. L1 and L2 participants showed a similar pattern of modulation

One of our most interested research questions is whether L2 learners could exhibit a similar tPBM enhancement pattern on sentence processing as in L1 speakers. The current study found that L2 showed a similar pattern of modulation with L1 speakers, with sentence processing ability improved after tPBM stimulation but not for non-sentential WM tasks. Previous research has found that L1 and advanced L2 could show parallel patterns for sentence processing (Bowden et al., 2013; Chen et al., 2023b; Steinhauer et al., 2009). For instance, Chen et al. (2023b) found that L1 and L2 with high proficiency level yielded quite similar ERP patterns in terms of interplay between syntactic and semantic processing. Bowden et al. (2013)'s work suggested that L2 learners could shift to native-like sentential processes with sufficient proficiency, exposure, and immersion. In addition, our study provided a piece of novel evidence for the aligned pattern regarding neuromodulation effects and causality mode.

These results are in line with the notion that both L1 and L2 speakers exploited LIFG for sentence processing. Studies have shown that LIFG plays an integral part in L2 sentence processing and yields large plasticity (e.g., Chen et al., 2019, 2021b, 2023a; de Vries et al., 2010; Luke et al., 2002; Nakagawa et al., 2022; Wartenburger et al., 2003). Results from studies adopting natural language materials converged on the fact that LIFG was required in the course of L2 sentence processing and learning (Luke et al., 2002; Musso et al., 2003; Nakagawa et al., 2022; Sakai et al., 2004; Wartenburger et al., 2003; Yusa et al., 2011). A study of L2 learning by Sakai et al. (2004) substantiated the neural plasticity by showing that the activation of LIFG was boosted after 2-month L2 (English) training and practice. The evidence from late L2 learners even found activation of LIFG to a higher extent than their L1 processing when participants read L2 sentences, showing that lower language proficiency led to higher brain calling (Luke et al. 2002; Wartenburger et al., 2003). The artificial grammar learning paradigm provided us with more insights into the neural basis of L2 syntactic learning (Bahlmann et al., 2008; Chen et al., 2021a; Friederici et al., 2006a; Grey et al., 2018; Liu et al., 2023; Morgan-Short et al., 2015). A novel artificial hierarchical syntactic structure-building grammar was developed by Chen et al. (2021a) and Liu et al. (2023), and demonstrated that the fundamental operation of merge rested on the function of BA 44 in LIFG. To sum up, sentence processing activates LIFG both for L1 and L2 reading, which shows large plasticity to be modulated, although some studies pointed out that L2 processing might involve more anterior regions in LIFG with lower automaticity (Jeon & Friederici, 2013).

4.3. Application prospect of tPBM on sentence processing

Consistent with former studies of neuromodulation (Hsu et al., 2014; Tseng et al., 2012), the current study found that participants with lower sentence processing ability at the initial state (i.e., prior to tPBM) were more susceptible to tPBM improvement. State-dependency was often used to explain the effects of brain stimulation concerning the initial state of stimulated regions (Hsu et al., 2014; Silvanto et al., 2008). For instance, TMS has been shown to be particularly effective on less active neurons (Silvanto et al., 2008). As for the current study, the state-dependent effect of neuromodulation techniques may become a feasible interpretation also for tPBM, that is, lower performers may have neurons less activated initially and thus show greater tPBM effects in return.

More importantly, the correlation between initial sentence processing performance and the degree of tPBM improvement broadened the prospect of tPBM applications. With the fact that tPBM was more effective for lower performers, the value of tPBM became more prominent by applying tPBM towards less-competent groups. Furthermore, we certified the positive modulation effect of tPBM on L2 learners, who served as the participants with lower (L2) complex sentence processing ability. The present findings, therefore, suggested that it might be possible to further apply tPBM to the upregulation of participants with language ability deficiency. Overall, the present study shed light on tPBM—a promising NIBS tool/approach—for its future clinical applications on the population struggling with language acquisition/learning difficulties, language impairments, or progressing language capacity declination. In the future, tPBM is expected to be a favorable alternative with relatively low cost and highly consistent enhancement effect to improve/facilitate the human language faculty.

4.4. Limitations

Although LIFG is acknowledged to play a key role in hierarchical syntactic structure construction, sentence processing also involves several other crucial brain regions such as the left posterior temporal cortex (LpTC; Chen et al., 2023a; Kinno et al., 2008) and is supported by a left-dominant fronto-temporal network (Friederici, 2017). In future research, we will attempt to change the locations of tPBM, stimulating language networks to better understand its causal role in complex sentence processing. However, regrettably, we must admit that the positioning precision of tPBM was relatively coarse. To maintain enough energy emitted to participants to induce metabolic and hemodynamic changes and to avoid causing burning to the skin, the area of the laser beam of tPBM should not be too small. For the present study's protocol, the irradiance of 150 W/cm^2 and the laser beam area of 13.57 cm^2 (4-cm diameter) were proven to be safe and effective by the prior studies (Li et al., 2023; Zhao et al., 2022). However, this extent of exposure area makes it hard to localize the target stimulated area precisely on the brain and to focalize the functions of finer brain areas (e.g., pars opercularis) as TMS did (e.g., Acheson & Hagoort, 2013). Nevertheless, as our first attempt, this study showed the neuromodulating effect of tPBM on the LIFG to improve complex sentence processing performance.

Moreover, the non-sentential verbal WM task was manipulated as an independent task and conducted separately in the present study, which aimed to investigate the mediating role of verbal WM related to the linear processing of unstructured sequences. To better investigate whether tPBM boost on sentence processing ability was attributed to the verbal WM necessary for hierarchical processing of structured sequences in the interpretive stage or not, it is recommended for future studies to manipulate WM as an independent variable or to adopt a comprehensive factorial design with various sentence types with different verbal WM loads to provide more insights. It is worth noting that some other cognitive operations (such as attentional control) are also recruited when processing complex sentences. It is recommended to compare the cognitive control tasks with the language tasks to further purify the causal role of LIFG in complex sentence processing via tPBM.

Furthermore, syntactically complex sentence processing is also accompanied by the difficulty of semantic interpretation, and given the evidence showing LIFG is also responsible for semantic processing (Hagoort, 2013), the enhancing effect on sentence processing might be related to the facilitation of both syntactic and semantic processing (i.e., unification). Future studies might employ jabberwocky sentences (e.g., Chen et al., 2023a; Fedorenko et al., 2012; Matchin et al., 2019) or artificial grammars (e.g., Bahlmann et al., 2008; Chen et al., 2021a; Liu et al., 2023) to further differentiate these internal linguistic processes.

Lastly, the neural mechanisms underlying the tPBM effects on behavioral performances of language/sentence processing remain unclear in the present. Future studies are expected to provide neuroimaging data and make further explorations and interpretations of the neural changes brought by tPBM.

5. Conclusion

The present study applied the novel NIBS technique—tPBM on LIFG to upregulate the sentence processing performances. As shown by the behavioral performance changes, tPBM improved the sentence processing ability in both L1 and L2 groups. Moreover, L1 and L2 participants showed a consistent enhancing pattern of tPBM that complex sentence processing performances were improved with no non-sentential verbal WM performance changes, suggesting tPBM's modulation on sentence processing might not be necessarily attributed to the verbal WM for unstructured sequences. It is also noteworthy that participants with lower initial sentence processing performances would benefit more from tPBM. Taking together, these findings supported the positive effectiveness of tPBM on high-level human cognitions and unprecedentedly extended tPBM's application to human language faculty as reflected by complex sentence processing performances; thus, such a promising and cost-effective NIBS tool is of great social and clinical significance for future applications.

CRediT authorship contribution statement

Mingchuan Yang: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Yang Liu:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Zhaoqian Yue:** Writing – review & editing, Data curation. **Guang Yang:** Writing – review & editing. **Xu Jiang:** Writing – review & editing. **Yimin Cai:** Writing – review & editing. **Yuqi Zhang:** Writing – review & editing. **Xiujie Yang:** Writing – review & editing, Supervision. **Dongwei Li:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Luyao Chen:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data, code, and materials of this study are available at https://osf.io/e35ac/. Further data and materials which also form other ongoing studies will be made available upon reasonable requests and collaborative agreement addressed to the co-authors by contacting the Max Planck Partner Group, School of International Chinese Language Education, Beijing Normal University, and signing a formal data-sharing agreement.

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