Running head: tDCS effect on bilingual language control

Transcranial direct current stimulation influences bilingual language control mechanism: evidence from cross-frequency coupling

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Abstract

How to better suppress the interference from the non-target language when switching from one language to the other in bilingual production? The current study applied transcranial direct current stimulation (tDCS) over the right dorsolateral prefrontal cortex (rDLPFC) to modulate language control measured by cross-frequency coupling. We found that switching to L2 was more modulated by F4-F3 alpha-beta phase-amplitude compared to switching to L1 after receiving the anodal stimulation at the language task schema phase. These findings suggest that anodal stimulation affects the selection of the target language task schema by enhancing the activation of frontal areas and facilitating the coordination between the left and the right frontal hemispheres. Altogether, tDCS influences language control during language switching.

Key words: language control; transcranial direct current stimulation; language switching; cross-frequency coupling

Introduction

Bilinguals often switch from one language to the other in response to the communication context. During bilingual language switching, the non-target language needs to be inhibited while the target language is being activated. Thus, the non-target language interferes the activation of the target language and the process of suppressing such cross-language interference is referred as language control[1-4]. Psycholinguists have been interested in understanding how to change such language control, namely, bilinguals' ability to switch between languages[1,2,5-7], because cross-language communication (e.g., language switching) involves dynamic interactions among a brain network responsible for language control. Recently, the transcranial direct current stimulation (tDCS), a noninvasive and safe cortical stimulation technique, has been used to effectively alter many cognitive functions by changing the polarity of a weak current flow[8-13]. Therefore, the current study aims to use the cross-frequency coupling to reveal the tDCS effect on language control.

According to the Inhibitory Control (IC) model, during language switching, inhibition works at either or both of the following two phases: 1) the phase of language-task selection (i.e., selecting an appropriate language in reference to contextual cues, e.g., L1, L2), 2) the phase of target-lemma retrieval (i.e., retrieving a target lemma by suppressing the non-target one, e.g., 苹果，apple)[1]. At either or both phases, the amount of inhibition is associated with language activation; that is, the greater the activation, the more the inhibition. When it comes to unbalanced bilinguals whose activation of L1 exceeds that of L2, more cognitive resources are required to inhibit L1 interference during L2 production. In the typical language

switching picture naming paradigm, for the reason that stronger inhibition on L1 during L2 production carries over to the next trial, it becomes more difficult to overcome such inhibition when switching back to L1. As a result, switching to L1 turns out to be longer than switching to L2 in reaction time measure, showing larger L1 switch costs than L2 switch costs. If bilinguals' ability to switch between languages could be influenced by external drive (e.g., tDCS), we are interested in how this would be applied to reduce the switch costs during language switching.

The anodal tDCS (A-tDCS) can depolarize cells and accelerate the transmission of information between neurons. On the contrary, the cathodal tDCS (C-tDCS) hyperpolarizes cells, thus slowing down the transmission of information between neurons. The sham tDCS (S-tDCS), as control stimuli, gives a shorter stimulation (30s), but allows participants to have the same subjective experiences as the real stimulation. It affects neither the cell membrane potential, nor the information transmission between neurons[14-17]. Hence, the A-tDCS may enhance participants' performance, while the C-tDCS weaken. The S-tDCS should produce effects somewhere between the A-tDCS and C-tDCS. However, previous studies demonstrated that cathodal stimulation did not always degrade cognitive performance[10,18,19]. Thus, existing researches mainly focus on whether tDCS is an effective stimulation method without dissociating the impact of different types of stimulation. The current study focuses on investigating whether tDCS has an influence on language control and what kind of effect will be produced upon stimulation.

Using the classic language switching paradigm to investigate language control[5,20-23], we asked unbalanced bilinguals to name pictures in L1 or L2 according to cues. Previous studies have found that the right dorsolateral prefrontal cortex

(rDLPFC) is responsible for suppressing unrelated stimuli[22,24,25]. Therefore, we applied tDCS over the rDLPFC during language switching to examine the effect of tDCS on language control. In addition, cross-frequency coupling (CFC) was analyzed because CFC reflects the process of transferring information from large-scale brain networks operating at behavioral timescales to the fast, local cortical processing required for effective computation and synaptic modification, thus integrating functional systems across multiple spatiotemporal scales[26]. As discussed earlier, unbalanced bilinguals need to suppress stronger interference from the non-target language (L1) when switching to the weaker language (L2). This stronger inhibition would lead to relatively stronger cross-frequency coupling due to information exchange in the frontal network, which is responsible for language control primarily focusing on the couple electrodes located on the frontal and parietal areas[27-30]. CFC is considered an effective analysis approach to reveal the language control mechanism across multiple spatiotemporal scales. Based on the frontal local cortex, we attempt to understand how language control is modified by effective computation and synaptic modification after receiving the tDCS[26].

Anodal or cathodal stimulation to the rDLPFC might change bilinguals' language control abilities to further affect the inhibition of cross-language interference. Our specific hypotheses are as follows:

1) tDCS affects the selection of the intended language task schema. Anodal or cathodal stimulation may enhance or weaken inhibitory control, and subsequently impact the process of selecting the intended language task schema, triggering stronger or weaker cross-frequency coupling when switching to L2 than to L1.
2) tDCS influences the retrieval of the target lemma. When switching to L2,

unbalanced bilinguals suppress the non-target lemma in L1, showing stronger or weaker cross-frequency coupling after receiving anodal or cathodal stimulation.

We hypothesize that the A-tDCS and/or C-tDCS affect language control by influencing the coordination between language control areas which can be measured by the cross-frequency coupling. By contrast, the S-tDCS does not exert influence on the language control areas, without showing CFC effect. At the theoretical level, the current study sheds light on how the frontal network is responsible for working collaboratively in language control to achieve cross-language communication.

Results

Behavioral results

Figure 2 shows the naming latencies and switch costs during bilingual picture naming. The statistical analysis showed a main effect of language: $F(1, 21) = 33.38$, $p < .001$, $\eta^2_P = .61$, with longer naming latencies for L1 (769 ± 17 ms) compared to L2 (728 ± 14 ms). Also, the main effect of language sequence reached significance: $F(1,21) = 155.93$, $p < .001$, $\eta^2_P = .86$, with longer naming latencies in switch trials (760 ± 15 ms) compared to repeat trials (737 ± 15 ms).

Insert Figure 2 about here.

We also observed a significant interaction between language switch costs and tDCS session: $F(2, 42) = 3.12$, $p = .060$, $\eta^2_P = .13$. A further analysis showed that L2 switch costs in the C-tDCS session (26 ± 20 ms) were larger than those in the S-tDCS session (12 ± 19 ms) only, but did not show any difference between the A-tDCS session and the C-tDCS session or between the A-tDCS session and the S-tDCS sessions: $F(2, 42) = 3.16$, $p = .005$, $\eta^2_P = .13$. In addition, L1 switch costs in the A-

tDCS (24 ± 26 ms) and C-tDCS (24 ± 28 ms) sessions did not differ from those in the S-tDCS session (32 ± 18 ms): $F(2, 42) = .86$, $p = .40$, $\eta^2_P = .04$. These results indicated that C-tDCS enabled L2 switch costs to increase, which was not observed in sessions applying A-tDCS or S-tDCS. These findings suggested that cathodal stimulation hindered the ability to switch from L1 to L2 for unbalanced bilinguals.

Cross-frequency coupling results

(1) Cue-locked different frequencies coupling

Insert Table 4 about here.

Table 4 shows an overview of the main effects of a variable and the interactions between variables. Statistical analyses exhibited a significant main effect of tDCS session, showing that alpha amplitude was more modulated by the theta rhythm. Among the three conditions of tDCS session, the strongest modulation occurred in the C-tDCS condition, followed by the A-tDCS condition and the sham tDCS condition. These effects occurred at 12 dyads of electrodes: F4-F5, FC2-FC5, FC2-FC3, F1-F6, F2-F5, F2-F1, F6-F5, F6-F2, F6-F6, FC3-FC2, FCz-FC2, FC4-FC2. The main effect of language was also significant at the couple electrodes of FC3-FC1, such that the beta amplitude of L1 trials was more strongly modulated by delta rhythm than that of L2 trials: $F(1, 21) = 12.36$, $p < .001$, $\eta^2_P = .31$.

A significant two-way interaction between language and language sequence was obtained, showing alpha/beta phase-amplitude coupling at the couple electrodes of

FC4-F1: $F(1, 21) = 9.73$, $p = .01$, $\eta^2_P = .26$. A further analysis showed that L2 switch trials were more modulated compared to L2 repeat trials: $F(1, 21) = 5.86$, $p = .02$, $\eta^2_P = .18$.

The three-way interaction of tDCS session × language × language sequence reached significance at 2 dyads of electrodes: F4-F3, $F(1, 21) = 8.19$, $p < .001$, $\eta^2_P = .25$; F4-F1, $F(1, 21) = 8.71$, $p < .001$, $\eta^2_P = .22$. The phase of the alpha rhythm modulated amplitude in the beta rhythm, with stronger modulation occurring in the L2 switch trials as compared to L1 switch trials in the A-tDCS session at F4-F3, *$F(1, 21) = 8.19$, $p = 0.01$, $\eta^2_P = .23$.* It was also true for F4-F1, *$F(1, 21) = 8.71$, $p = 0.01$, $\eta^2_P = .24$.*

Insert Figure 3 about here.

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(2) Stimulus-locked different frequencies coupling

Insert Table 5 about here.

Table 5 shows an overview of the main effects of a variable and the interactions between variables. Statistical analyses showed a significant main effect of tDCS session, indicating that alpha amplitude was more modulated by the beta rhythm. Among the three conditions of tDCS session, the strongest modulation occurred in the C-tDCS session, followed by the A-tDCS session and the S-tDCS session. These effects occurred at 5 dyads of electrodes: FC1-FC2, FC1-FC4, FC2-FC2, FC2-FC4, FC4-FC1.

Taken together, the tDCS effect was observed at the two phases of language

switching. That is, during the A-tDCS session, switching to L2 was more modulated by alpha-beta phase-amplitude compared to switching to L1; and such modulation was coordinately achieved by both right and left frontal areas (e.g., F4-F3, F4-F1). By contrast, increased L2 switch costs were observed in the cathodal stimulation session compared to the sham session; however, this modulation in CFC was absent. This suggests that cathodal stimulation may weaken language control abilities in unbalanced bilinguals. Thus, these results indicate that tDCS produces an effect on language control during language switching.

Discussion

The current study investigated the effect of tDCS on language control by applying tDCS over the rDLPFC during language switching. To summarize our main findings, at the language task schema phase (i.e., cue processing), the A-tDCS exerted an effect on language control, that is, switching to L2 was more modulated by alpha-beta phase-amplitude compared to switching to L1, and such modulation was coordinately achieved by both right and left frontal areas. However, this modulation failed to be observed in the behavioral naming latencies. By contrast, the C-tDCS enabled L2 switch costs to increase**,** making it harder for L2 switching without modulation in cross-frequency coupling. These findings suggest that tDCS influenced the selection of target language task schema.

Anodal stimulation affects language control at the language task schema phase

The current study found that the A-tDCS influenced the selection of target language task schema, by showing more modulation of alpha-beta phase-amplitude in L2 switch trials compared to L1 switch trials. These results imply that the A-tDCS increases the excitation of frontal area (F4-F3), affecting unbalanced bilinguals' language control. Previous evidence suggested that bilateral inferior frontal gyri (i.e.,

left and right inferior frontal gyrus) are responsible for suppressing automatic processes and controlling interference from irrelevant information (such as prepotent responses from the dominant language)[28]. Specifically, the left prefrontal cortex is more related to response selection and its right counterpart is rather associated to response inhibition[31]. In the current study, we stimulated the rDLPFC and analyzed cross-frequency coupling at both right and left frontal electrodes. Although tDCS was applied on the right frontal electrodes, the left frontal processing was influenced because both bilateral frontal electrodes (F4-F3) belonged to the same language control area, and such influence was indexed by cross-frequency coupling.

On one hand, as demonstrated by earlier researches, alpha activity reflects inhibition of task-irrelevant networks[32-34]. Its activity thus plays an important role in limiting attention to targeted stimuli and blocking processing of irrelevant events[32].In this logic, bilingual participants needed to inhibit the interference from the non-target language task schema of the previous trial, and more inhibition was required when switching from L1 to L2. On the other hand, some studies suggested that beta activity represents the active maintenance of the current network configuration[35-37].Participants in our study may need to maintain the target language task schema to name pictures in the subsequent phase. Taken together, the inhibition-related alpha activity in combination with the maintenance-related beta activity coordinately completed the selection of the target language task schema, showing stronger cross-frequency coupling in alpha-beta amplitude-phase when switching from L1 to L2 than vice versa. However, we did not find reduced or increased L1/L2 switch costs in the A-tDCS session, therefore, it is inclusive whether such cross-frequency coupling reflects effective suppression.

In short, A-tDCS affects the process of selecting the target language task schema

by enhancing the activation of frontal areas to impact the coordination between the right and left frontal hemispheres. However, we did not observe obvious decreasing in L2 switch costs in the A-tDCS session in the behavioral data.

Cathodal stimulation hinders the selection of the target language task schema

According to previous studies, the C-tDCS inhibited the activity in cortex areas[14,15,38] as predicted, increased L2 switch costs were observed in the C-tDCS compared to the S-tDCS session, while modulation was absent when switching to L2 compared to switching to L1. As frontal areas were inhibited in C-tDCS, unbalanced bilinguals failed to allocate language control resources to suppress the interference from the non-target language task schema of the previous trials. Thus we did not find the cathodal effect in the high temporal resolution analysis of cross-frequency coupling. Taken together, cathodal stimulation inhibited the frontal areas which were related to language control, as a result, L2 switch costs in the C-tDCS session were larger than those in the S-DCS session.

As cathodal stimulation suppressed the frontal activity, we wonder why L1 switch trials didn't generate pronounced behavioral difference between the C-tDCS, A-tDCS and S-tDCS sessions, like L2. We reason that unbalanced bilinguals are more automatic in processing their native language and this process was not affected by temporary excitation or inhibition on the frontal areas. Therefore, there was little difference in L1 switch costs in both A-tDCS and C-tDCS sessions compared to the S-tDCS sessions. Another possibility is that L1 located in the left inferior frontal gyrus (Broca's area 44, a critical region for speech production)[39,40]was not affected by the stimulation on the right frontal areas. Thus, this stimulation didn't affect L1 processing. Future study could devote to resolving the above issues by investigating the tDCS effect on balanced bilinguals to minimize L2 proficiency confound.

Conclusion

The current study employed tDCS to influence language control by using cross-frequency coupling analysis. We found that both right and left frontal areas worked collaboratively to select the target language task schema during bilingual language switching under the anodal stimulation, probably due to suppressing the interference of the non-target language task schema.

Method

Participants

We recruited 31 bilingual undergraduates from Liaoning Normal University. All of them were right handed with normal or corrected-to-normal vision, reporting neither history of neurological/psychological impairments nor receiving treatment with any psychoactive medication. Prior to the experiment, they signed the written informed consents. The research protocol was approved by the Institutional Review Board at the School of Psychology, Liaoning Normal University. All methods mentioned in this research were performed in accordance with the relevant guidelines and regulations. Data from 9 participants were eliminated due to excessive EEG artifacts. The final sample for analysis consisted of 22 participants (9 male), aged from 18 to 26 years old ($M = 21.04 \pm 2.2$ years).

Table 1 presents the age of L2 acquisition (AOA), the self-evaluated language skills (6-point scale: 1 = “quite poor”, 6 = “highly proficient”) and results from L2 proficiency test. In measuring the self-rated language skills, paired-sample t-test indicated that the proficiency ratings of L1 and L2 for all four skills were significantly different: listening, $t(22) = 12.09$, $p < .001$; speaking, $t(22) = 8.83$, $p < .001$; reading, $t(22) = 6.75$, $p < .001$; writing, $t(2) = 5.25$, $p < .001$. These results demonstrated that the bilingual participants’ proficiency of Chinese and English were

significantly unbalanced. Furthermore, they were tested with two objective proficiency tests: LexTALE (maximum score of 100 points) and the Oxford Placement Test (OPT, maximum score of 50 points)[41,42]. The average L2 proficiency was reported in Table 1.

Insert Table 1 about here.

Language switching materials

We adopted the picture-naming task during language switching. The stimuli consisted of 72 line-drawing pictures (15cm × 15 cm) selected from the picture database of Snodgrass and Vanderwart's photo gallery standardized by Zhang and Yang[43].The Chinese names of all pictures were two-character words, and their English equivalents were either one- or two-syllable words with 3-6 letters. In order to guarantee similar familiarity between the L1 and L2 picture names, another group of 35 intermediate proficient Chinese (L1)–English (L2) bilinguals who did not participate in the current experiment performed familiarity rating (5-point scale; 1 = "very unfamiliar", 5 = "very familiar"). In the average subjective familiarity, no significant difference was found between L1 and L2 (L1: 4.85 ± .08, L2: 4.84 ± .12, $t(34) = .69$, $p = .76$).

The selected seventy-two pictures were equally randomized into three sets for each stimulation session (i.e., A-tDCS session, C-tDCS session, and S-tDCS session). Thus, for each participant, there was no repetitive picture across three stimulation sessions. There was no difference in the familiarity of the L1 and L2 picture names in

each session (see Table 2). A repeated-measure ANOVA was further conducted among the three sessions, and there was no difference between different sessions, either: $F(2, 46) = .36$, $p = .64$.

Insert Table 2 about here.

Procedure

Transcranial direct stimulations (tDCS)

This study consisted of three sessions: anodal (A-tDCS), cathodal (C-tDCS) and sham (S-tDCS) stimulation. The tDCS was delivered by a battery-driven direct current stimulator (ActivaDose□Iontophoresis Delivery Unit, USA). The procedure of our study is presented in Figure 1. The order of stimulation (anodal, cathodal or sham) was fully counterbalanced across participants. For each session, after stimulation, participants were instructed to do picture naming in either L1 or L2. In addition, each session was separated by at least 7 days. For example, participant A first received the anodal stimulation and then completed a language switching task in picture naming. 7 days later, Participant A received the cathodal stimulation and completed the second language switching task with a different set of pictures. Again, after another 7 days, the sham stimulation was delivered to Participant A followed by the final language switching task with the third set of pictures.

Insert Figure 1 about here.

Stimulation electrodes were surrounded by a flat sponge soaked in an isotonic NaCl solution and coated with Aqua Sonic ™ ultrasound transmission gel to ease skin irritation. The A-tDCS was delivered over rDLPFC via a 5cm × 5cm electrode placed halfway between the EEG electrode sites for F4 of the 10-20 EEG system, fixed by the rubber belt. The extra-encephalic C-tDCS reference electrode (5cm × 5cm), proven safe in healthy subjects[44], was affixed to the right shoulder with a skin-friendly cello type. Before the EEG experiment, a constant direct current of 1 mA was applied for 25 minutes. During S-tDCS, the procedure was the same, except that the tDCS was turned off after 60 seconds during both the pre-experimental and experimental tDCS. At the beginning and the end of each tDCS session, there was a ramping period of 10 seconds. The study design was single-blinded, such that participants were kept naïve about when and how often each tDCS was applied. Potential tDCS side effects were assessed with a questionnaire (see below) at the end of each session[8].

Language switching procedure

After receiving tDCS stimulation during each session, participants were encouraged to have the L1 and L2 picture names familiarized in order to minimize naming errors. In the formal experiment, stimuli were presented at the center of a 17-inch computer screen with 1024 × 768 pixel resolution. At the beginning, a naming cue (red or blue square) appeared for 250ms. The color-language associations were counterbalanced across participants to avoid color preference. Specifically, half of participants used L1 to name the picture if a red square was presented as a cue while a blue cue indicated that participants should name the picture in L2. For the other half, the color-language association was reversed. After the cue, a blank screen

appeared for 500 ms, followed by a picture as stimulus. Both naming speed and accuracy were emphasized. The picture would disappear immediately after naming or after 2000 ms upon no response. Finally, a blank screen appeared for 1000 ms before a new trial started.

Two types of trial sequences appeared randomly: switch trials and repeat trials. In the repeat trials, the language used in the current trial was the same as that of the previous trial (L1L1 or L2L2); whereas in the switch trials, the response language between the current and the previous trial was different (L1L2 or L2L1). There were 5 blocks per session. Each block contained 24 repeat trials of both L1L1 and L2L2, as well as 24 switch trials of L1L2 and L2L1. All stimuli were presented pseudo-randomly. The same picture appeared twice in each block and participants were asked to name the picture in L1 or L2 based on the cue. Participants couldn't predict the following language or picture during the experiment and no more than 3 continual trials were named by the same language. Prior to the formal experiment, participants performed 12 practice trials and their response times were recorded by a PSTSR-BOX connected to a microphone.

Electrophysiological recording

Electrophysiological data were recorded by a set of 64 electrodes from eegmagine (ANT Neuro) according to the extended 10-20 positioning system. The signal was recorded with a 1 kHz sampling rate and referenced online to the CPZ electrode. The electrodes M1 and M2 were separately placed on the left and right mastoids, respectively. Impedances were kept below 5 kΩ. The sampling rate was reduced to 500 Hz in offline processing. The offline data was referenced to the average of M1 and M2. EEG activity was filtered online with a bandpass between 0.1 and 100 Hz and re-filtered offline with a 30 Hz, low-pass, zero-phase shift digital

filter. Ocular artifact reduction was performed through ICA component rejection by using EEGLAB[45].Other movement artifacts were identified by visual inspection and manually removed. Continuous recoding was segmented into cue-locked -100 to 600 ms epochs and stimulus-locked -100 to 650 ms to dissociate each phase of language switching. Correspondingly, the epochs were referenced to the 100 ms pre-cue baseline, and the 150 ms pre-stimulus baseline. Signals exceeding ±80 μV in any given epoch were automatically discarded.

Behavioral data analysis

The overall naming accuracy of the naming tasks was quite high (>95%), so it was not included in further analysis. We removed the data from the first two trials in each block, as well as incorrect responses and data from naming latencies beyond *M* ± *3SD*. For naming latency, a three-way repeated-measure ANOVA was conducted with three within-subject factors: tDCS session (A-tDCS, C-tDCS, S-tDCS), language (L1, L2), and language sequence (repeat, switch).

tDCS stimulation questionnaire

We assessed possible stimulation-induced perceived sensations using a translated and adapted version of the standardized questionnaire[8]. Items of this questionnaire, which represent distinct perceived sensations respectively, were chosen with respect to possible tDCS side effects[46]. Participants were encouraged to evaluate the intensity of each sensation item on a 5-point scale (1 = “none”, 5 = “strong”), about whether the sensation influenced their performance, as well as when the influence started and terminated (beginning = “1”, middle = “2”, end = “3” of the experiment). Finally, subjects provided their judgments of perceptual sensation concerning the stimulation condition using five categories: no stimulation/ only beginning/ only at the end/ during the whole experiment/ others. In a nutshell, the

questionnaire was used to measure differences between the stimulation conditions so as to evaluate the effectiveness of stimulation. To test the difference between stimulation conditions, one-way ANOVA was conducted for each sensation item. As shown in Table 3, there was no difference between conditions.

Insert Table 3 about here.

Analysis of Cross-Frequency Coupling

To evaluate the rhythm's modulation on amplitude, we calculated the modulation index (MI) based on the standard measures previously described in Canolty et al[47]. The MI was considered a reflection of the coupling between different frequencies which interested us. We used F1-A (high frequency amplitude) to express the amplitude and F2-P (low frequency phase) to represent frequency phase. The MI calculation procedure was as follows.

1) The eegfilter function in EEGLAB was used to go through band-pass filter, and two different frequency signals were extracted: low-frequency and high-frequency signals[48].

2) Hilbelt Transform was applied to calculate both the instantaneous amplitudes and phase of the signal[49,50].

$\zeta(t) = s(t) + i\bar{s}(t)$

$\zeta(t)$: row signal

$s(t)$: real part of the signal

$i\bar{s}(t)$: imaginary part of the signal

$$\bar{s}(t) = H(s) = \frac{1}{\pi}\int_{+\infty}^{-\infty} \frac{s(\tau)}{n-\tau}\, d\tau$$

$\bar{s}(t)$: the signal transform by Hilbelt

$$A(t) = \sqrt{s(t)^2 + \bar{s}(t)^2}$$

$$\varphi(t) = \arctan\frac{s(t)}{\bar{s}(t)}$$

$A(t)$: instantaneous amplitude of the signal

$\varphi(t)$: instantaneous phase of the signal

3) The high frequency amplitude and the low frequency phase were combined to create a new complex signal: z = hf_amplitude.*exp (1i*lf_phase).

Z: a new signal

hf_amplitude: amplitude of high frequency

lf_phase: phase of low frequency

$$z[t] = a_2[t]e^{i\varphi 1[t]}$$

$a_2[t]$: instantaneous amplitude of high frequency

$e^{i\varphi 1[t]}$: instantaneous phase of low frequency

$z[t]$: *a* new composite signal

4) The mean of the new complex signal was computed: z_mean = mean(z), and the mean amplitude was calculated by the MATLAB function 'abs ()' to get the 'MVL-MI' (The mean vector length modulation index, MVL-MI (MI_{raw}) = abs (z_mean)).

$$MI_{raw} = |\frac{1}{N}\sum_{t=1}^{N} z[t]|$$

5) To attain surrogate data, we had to randomize the instantaneous amplitudes of high-frequency signals[47].The following was how we did this: first, in order to divide the whole time series into two slices, we randomly selected one time point (n) from the time series (old); next, the position of two slices were exchanged to get a new time series, and a new MVL-MI was also calculated. This procedure ran over and over for one hundred times to calculate the means and standard deviations of all these MVL-MIs.

A normalized MVL-MI was obtained by the raw MVL-MI, the mean and standard deviation of these new MVL-MIs41[36].

$$M = (M_{raw} - \mu)/\sigma$$

M: normalized MVL-MI

M_{raw}: row MVL-MI value

μ: the mean of these new MVL-MI

σ: the standard deviation of these new MVL-MI

By this procedure, we obtained the cross-frequency coupling. In order to avoid false-positive results, an FDR[51,52]correction (q = .05) was applied for p values of ANOVA in all couples of electronic points in each condition and each coupling frequency band.

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Author Contributions

J.T., and H.L. designed research; J.T., C.K., and B.L. performed the research and analyzed the data; H.L., X.W., J.T., and Y.H. wrote the paper. Besides, all authors reviewed and commented on the manuscript.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests: The authors declare that they have no competing interests.

Table and Figure Captions

Table 1.

	L1(Chinese)	L2(English)
Self-rating		9.00(2.16)
AOA		
Listening	5.50(.67)	3.41(.80)
Speaking	4.86(.77)	3.18(.85)
Reading	4.50(1.37)	2.73(.88)
Writing	4.36(1.09)	2.95(1.36)
Proficiency test		
LexTALE		36.00(9.97)
OPT		36.55(3.97)

Table 2.

	L2	L1	t
A-tDCS	4.86 (.08)	4.83 (.15)	.86
C-tDCS	4.85 (.08)	4.86 (.07)	-.24
S-tDCS	4.84 (.10)	4.86 (.10)	-1.04

Table 3.

Items	A- tDCS	C- tDCS	S- tDCS	F
Itchiness	1.77 (.97)	1.64(.79)	1.64 (.79)	1.54
Pain	2.09 (1.02)	2.32 (1.00)	2.09 (1.11)	.68
Burning	1.45 (.67)	1.50 (.80)	1.32 (.57)	.71
Warmth/heart	1.32 (.57)	1.41 (.59)	1.32 (.57)	.32
Pinching	1.41 (0.73)	1.45 (.60)	1.32 (.57)	.53
Iron taste	1.00 (.00)	1.05 (.21)	1.05 (.21)	1.00
Fatigue	1.59 (.73)	1.50 (.67)	1.59 (.80)	.24
Effect of performance	1.68 (.57)	1.45 (.60)	1.41 (.67)	1.51
Start	1.55 (.74)	1.82 (.80)	1.45 (.67)	2.41
End	1.68 (.78)	1.73 (.70)	1.45 (.60)	2.56

Table 4.

Main/Interaction effect	Electrodes	F	p	η^2_P
tDCS session	FC2-FC5	5.19	.01	0.16
tDCS session	FC2-FC3	9.64	.00	.26
tDCS session	F1-F6	3.82	.03	.12
tDCS session	F2-F5	8.07	.00	.23
tDCS session	F2-F1	4.67	.01	.15
tDCS session	F6-F5	6.70	.00	.16
tDCS session	F6-F2	4.20	.02	.13
tDCS session	F6-F6	6.08	.00	.18
tDCS session	FC3-FC2	5.53	.01	.17

tDCS session	FCz-FC2	5.28	.01	0.16
tDCS session	FC4-FC2	4.76	.01	0.15
Language	FC3-FC1	12.36	.00	0.31
Language × Language sequence	FC4-F1	9.73	.01	.26
tDCS session × Language × Language sequence	F4-F3	8.19	.00	.24
tDCS session × language × language sequence	F4-F1	8.71	.01	.23

Table 5.

Main/Interaction effect	Electrodes	*F*	*p*	η^2_P
tDCS session	FC1-FC2	8.90	.02	.14
tDCS session	FC1-FC4	5.30	.01	.16
tDCS session	FC2-FC2	6.67	.00	.20
tDCS session	FC2-FC4	4.24	.02	.14
tDCS session	FC4-FC1	4.20	.02	.13

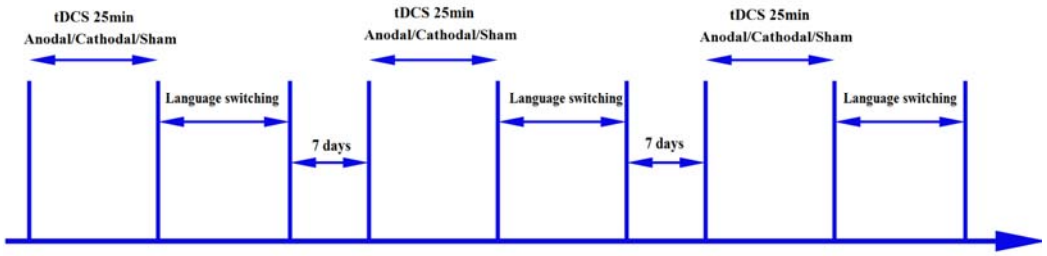

Figure 1

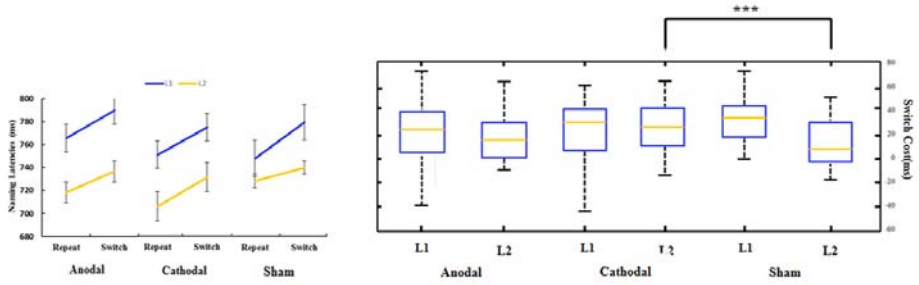

Figure 2

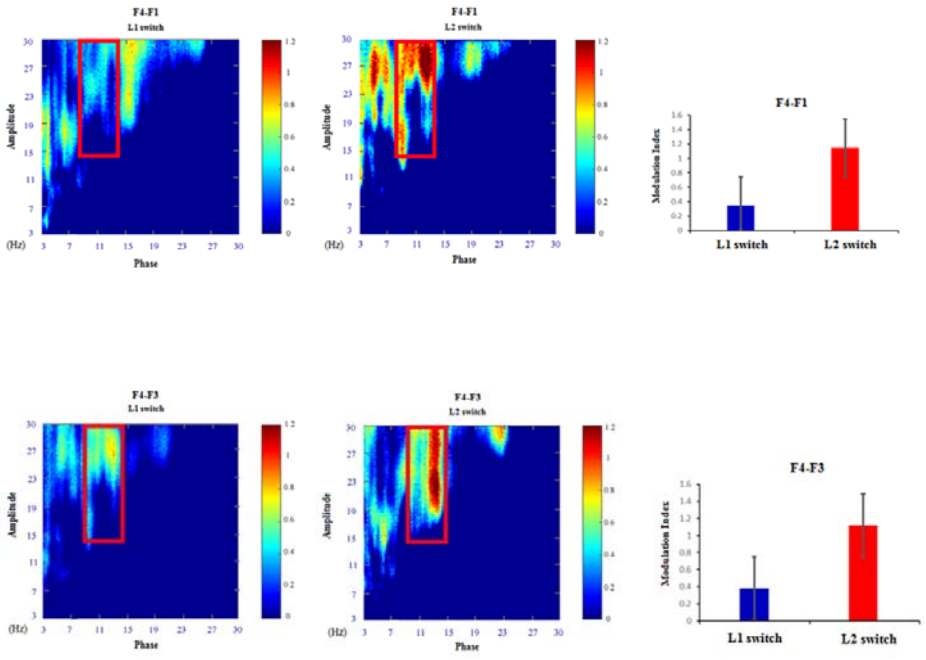

Figure 3