

Anodal transcranial direct current stimulation over the left temporoparietal cortex facilitates assembled phonology



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ABSTRACT

Introduction: A major challenge in learning to read an alphabetic language is to learn to map graphemes to phonemes (i.e., assembled phonology). Previous imaging studies have revealed that the left temporoparietal cortex (LTPC) is associated with assembled phonology, the causal role of LTPC in assembled phonology and tDCS's short- and long-term facilitation effect on reading via assembled phonology are not clear.

Methods: Two matched groups of native Chinese speakers received anodal tDCS either on LTPC or the visual cortex before they were trained to read an artificial language. All participants learned two sets of words, one through assembled phonology and the other through addressed phonology.

Results: We found that tDCS on LTPC specifically facilitated learning via assembled phonology, but not that via addressed phonology. Furthermore, the beneficial effect was still present four days later.

Conclusions: Repeated applications of tDCS at LTPC had long-term benefits on assembled phonology. These results have both theoretical and practical implications for learning to read.

1. Introduction

Reading is an integral part of life in this information age, but across countries, between 5% and 15% of the population suffer from reading difficulties (i.e., dyslexia) [1–4]. It is therefore imperative to understand the mechanisms underlying learning to read. A critical component of reading is to access the phonology of the words from their visual forms. Behavioral, neuropsychological, and computational modeling studies have identified two distinct routes of phonological access [5–7]. Assembled phonology (the indirect route) transforms visual words into phonology through grapheme-to-phoneme correspondences (GPC), and is mainly used to read shallow orthographies, such as Italian and German. In contrast, addressed phonology (the direct route) accomplishes phonological access via direct associations between the visual forms of words and their sounds, and is mainly used to read deep orthographies, such as Chinese. For most languages including English, both routes operate in parallel but the degree of their engagement varies by the regularity and familiarity of the words. Specifically, assembled phonology is mainly used to read unfamiliar but regular words (e.g., fyfot) and pseudowords (e.g., pog), whereas addressed phonology is mainly used to read familiar words (e.g., go) and exception or

irregular words (e.g., pint) [5,8].

Previous studies that compared addressed and assembled phonology have shown both universal and language-specific cognitive factors in early literacy development [9]. These studies used different reading materials: transparent (e.g., German) versus opaque orthographies (e.g., Chinese) [10–12], more transparent alphabetic (e.g., Italian) versus less transparent alphabetic languages (e.g., English) [13–17], and regular versus irregular words [18]. For instance, it was found that, rapid automatized naming was a more important predictor of reading development in transparent than in opaque orthographies [11,12]. Previous studies also reported that speeded naming was associated with reading of both regular and irregular words, but phonological awareness was only associated with recognition of regular words, whereas morphological awareness only with recognition of irregular words [18]. In sum, there is a clear distinction in cognitive basis of addressed and assembled phonology.

Neuroimaging studies have highlighted the role of the LTPC in assembled phonology. This brain region is more activated by pseudo words than familiar words [19–24], orthographically regular words than irregular words [20,22,25], and alphabetic than logographic writing systems [26–30]. This region's role in assembled phonology was

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also confirmed in a study that used a parametric design to manipulate word frequency, spelling-sound consistency, imageability, length in letters, bigram frequency, and biphone frequency [31]. A large-scale imaging study has further linked individuals' word decoding ability (a measure of assembled phonology) with their gray matter volume in the LTPC [32]. Finally, many studies have shown that English-speaking children with developmental dyslexia are mainly impaired in assembled phonology and show functional deficits in the LTPC [33–35].

In addition to natural languages, artificial language has also been used to study the neural basis of phonological access and results confirmed the role of the LTPC in assembled phonology [36,37]. In these studies, two groups of subjects were trained to read an artificial language either through addressed or assembled phonology. Functional MRI scans at the end of training revealed greater activation in the LTPC in the assembled than addressed group during both naming and perceptual tasks [37]. They further found that compared to native English speakers, native Chinese speakers were slower at learning assembled phonology and showed weaker activation in the LTPC [36]. This result corroborates previous findings that Chinese readers experience difficulties in assembled phonology when learning to read English [38], and show weaker activation in the LTPC compared to native English speakers when reading English [39].

Although the above studies using fMRI and the artificial language training paradigm have implicated LTPC in assembled phonology, their results were correlational in nature. To substantiate a causal role of LTPC in assembled phonology, it is necessary to use a non-invasive brain stimulation technique such as transcranial direct current stimulation (tDCS) or transcranial magnetic stimulation (TMS) [40,41]. Using tDCS, several studies have found that stimulation on LTPC facilitated language learning [42]. For instance, studies using a statistical learning paradigm found that tDCS on the LTPC facilitated the learning of nonword-picture pairings in healthy subjects [42], and the retrieval of newly-acquired picture names in healthy subjects and participants with aphasia [43]. Using similar tasks and anodal tDCS over five consecutive days, another study revealed beneficial effects on word learning both immediately following stimulation and one week after the last stimulation session [44].

The present study aimed to examine whether LTPC is causally linked to assembled phonology, using an artificial language training paradigm in combination with tDCS. Two matched groups of participants received anodal stimulation either on LTPC or on the control site (the visual cortex, VC) prior to training. Effects on both immediate learning and long-term maintenance several days after training were evaluated. We used High-Definition tDCS (HD-tDCS) with small disk electrodes in 4×1 ring configuration, which delivered more focalized stimulation than the conventional tDCS with large rectangular electrodes (mostly 35 cm^2) [45–50]. We hypothesized that tDCS at LTPC would specifically facilitate learning words via assembled phonology, but not that via addressed phonology. We also expected that the beneficial effect of tDCS would last several days.

2. Methods

2.1. Participants

Forty-eight native Chinese speaking college students participated in this study. Data from two participants were incomplete due to computer errors and were deleted. The final sample of 46 participants (22 males) had a mean age of 19.67 ± 1.81 years old, ranging from 18 to 25 years. None of the participants had previous experience with Korean language, from which we created the artificial language (see below). All participants had normal or corrected-to-normal vision, had no previous history of neurological or psychiatric disease, and were strongly right-handed as judged by Snyder and Harris's handedness inventory [51]. The 46 participants were divided into two groups to receive anodal tDCS either on the LTPC or the VC. The two groups were matched on

Table 1
Background characteristics of the LTPC and VC groups.

Variables	LTPC	VC	t	p
Age	19.61 (1.95)	19.74 (1.71)	-.24	.81
Gender (M/F)	11/12	11/12	.00	1.00
Visual-auditory learning	127.43 (5.34)	128.61 (4.62)	-.79	.43
Sight word efficiency	75.15 (8.32)	75.43 (7.69)	-.12	.91
Phonemic decoding efficiency	45.35 (7.35)	45.07 (6.30)	.14	.89
Memory of digits	22.57 (2.39)	22.17 (2.44)	.55	.59

Note: Numbers inside the parentheses represent standard deviations. The scores for all tests are the number of correct items. Visual-auditory learning is a subtest of the Woodcock Reading Mastery Tests-Revised (WRMT-R); sight word efficiency and phonemic decoding efficiency are subtests of the Test of Word Reading Efficiency (TOWRE); memory of digits is a subtest of the Comprehensive Test of Phonological Processing (CTOPP).

age, gender, and reading skills in terms of visual-auditory learning as measured by the Woodcock Reading Mastery Tests – Revised (WRMT-R) [52], phonemic decoding efficiency and sight word efficiency as measured by the Test of Word Reading Efficiency (TOWRE) [53], and memory ability as measured by the memory of digits from the Comprehensive Test of Phonological Processing (CTOPP) [54] (Table 1). Informed written consent was obtained from the participants before the experiment. The training and tDCS procedures were approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University.

2.2. Materials

An artificial language was created based on 144 visual forms of Korean Hangul characters [55]. By pairing these visual forms with auditory word forms in two different ways, we created words to be read in assembled phonology and words to be read in addressed phonology. For the former, letters corresponded with phonemes in the international phonetic inventory (IPA), thus following perfect GPC rules. For the latter, there was no correspondence between letters and phonemes, so each of the words had to be read as a whole.

144 artificial language words were created to be read in assembled phonology. Half of these words consisted of two letters (one consonant plus one vowel, i.e., CV) which had either a left-to-right or top-to-bottom spatial configuration, the other half of the words consisted of three letters (Consonant-Vowel-Consonant, i.e., CVC) which had an either left-right-bottom or top-middle-bottom configuration (Fig. 1A and B). These words were divided into two sets of 72, with each set being constructed using 12 different Korean Hangul letters, including 6 consonants and 6 vowels. All these phonemes were chosen from the IPA and difficult phonemes were avoided. To confirm our judgment, three native Chinese-speaking graduate students were recruited to rate how easy it is to pronounce these phonemes on a scale of 1 (very difficult to pronounce) to 5 (very easy to pronounce). The average scores were higher than 3 for all phonemes (mean = $4.43 \pm .78$). The words to be read in addressed phonology were created based on those assembled words by shuffling the pairings of the visual word forms and the phonological word forms within each set, thus demolishing the GPC rules. The assignment of the two sets of words to the training conditions was counterbalanced across participants.

For both assembled and addressed words, each set of 72 words was further divided into six matched sub-groups, 12 words in each. For a given participant, one group was used as the target words for training, and the other five groups were used for tests in the five runs (more details in the section of Procedures of Training and Testing). For both training conditions, each subgroup was used equally often as the trained targets across the participants. Across sets and sub-groups, words were matched on the number of strokes (mean = 6.28 ± 1.92 , with a range from 2 to 11), number of units (mean = $2.50 \pm .50$, with a

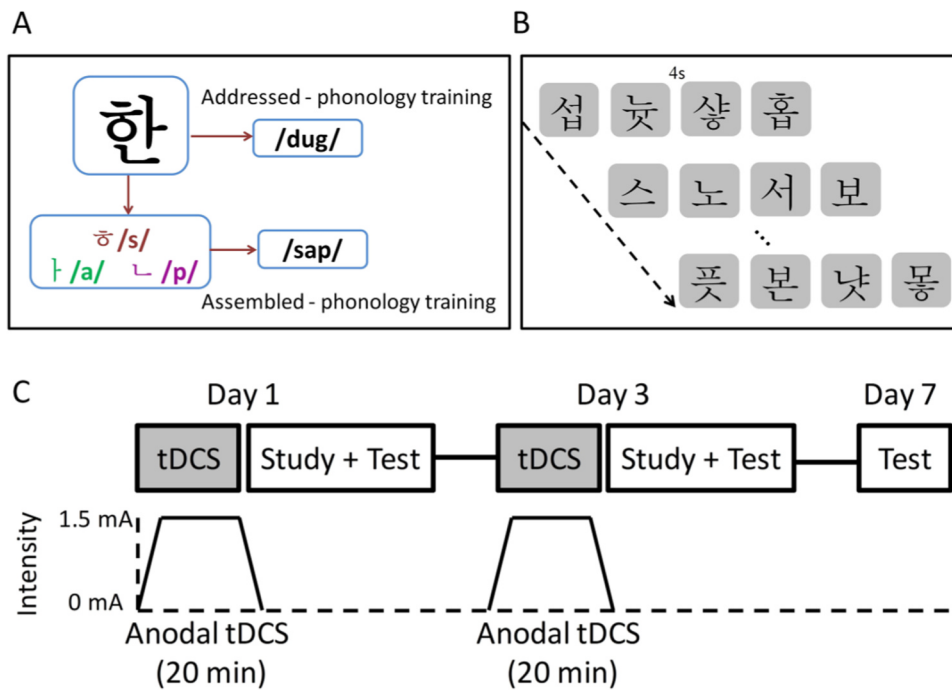


Fig. 1. Experiment design and examples of the stimuli. (A) Two training conditions were used for participants to receive addressed and assembled phonology training. (B) The word choice test after the learning task in each run. (C) The training schedule. Participants completed the training program after tDCS stimulations on two days, separated by 1 day, and completed the test one week after training.

range from 2 to 3), and spatial structure (left-right vs. top-bottom).

The visual forms of the artificial language words on the computer screen were in 151×151 pixels in size, subtending 1.3° visual angle. The sounds of these words were read by a native Chinese female speaker. All the sounds were denoised and normalized to the same length (800 ms) and loudness using Audacity 1.2.6 (<http://audacity.sourceforge.net>).

2.3. Procedures of training and testing

Both the LTPC and VC groups learned both addressed and assembled phonology (Fig. 1A). The training consisted of three sessions, spanning seven days (Fig. 1C). Session 1 (day 1) and Session 2 (day 3) shared identical procedures, consisting of the anodal tDCS being applied at the designated site and four runs of training following the stimulation. The four training runs consisted of two for addressed phonology and two for assembled phonology in an interleaved manner (addressed-assembled-addressed-assembled, or assembled-addressed-assembled-addressed). For both the LTPC and VC groups, the specific ordering of these two training conditions was counterbalanced across participants using an ABBA design. Session 3 (day 7) consisted of post-test only to measure long-term maintenance of the tDCS effect on assembled phonology four days after the last stimulation session.

Each run of training consisted of the learning task and the word choice test (Fig. 1B). The word choice test functioned both as an assessment and facilitator of learning. In each trial of the learning task, the visual form of a word was presented in the center of the computer screen and its pronunciation was presented auditorily through the headphones. Participants were asked to look carefully at the visual word form and listen to its pronunciation. To ensure that participants were awake and attentive, they were instructed to repeat the pronunciation aloud into the microphone. In each of the training trial, the visual word would stay on the screen for 3.5 s, and the next trial would start following a 1-second blank screen.

The requirements on learning differed between the two conditions. In the addressed training condition, participants were asked to memorize each of 12 trained words as a whole. Critically, as mentioned before, no GPC rules were implemented in this condition and thus addressed phonology was the only way to read these words. For the

assembled training condition, participants were asked to memorize the association between each word and its pronunciation by assembling the pronunciation of each letter in the designated order (left-to-right, top-to-down). At the beginning of the experiment, participants were taught explicitly to segment the word's pronunciation into phonemes and then pair each phoneme with the corresponding letter (Fig. 1A), but they were not taught the letters' pronunciations directly.

In the word choice test, each trial consisted of one word auditorily presented through the headphones and four words visually presented from left to right in the center of the computer screen. Participants were asked to indicate which word on the screen matched the sound they heard by pressing one of the four keys (D, F, J, or K) on the keyboard. The visual words would stay on the screen for 4 s, and the next trial would start following a 1-second blank screen. Participants were asked to respond as fast and accurately as they could, and responses made after the visual words disappeared were coded as errors and excluded from the final analysis.

As mentioned before, each run of the word choice test also included one subgroup of untrained words. This was useful for the assembled condition only, in which testing on the untrained words helped evaluate the learning of the GPC rules. Untrained words were also included in the addressed condition, merely for the sake of matching with the assembled condition. However, as such words were not pronounceable in the addressed condition, participants were told that they could make a random response to them in the word choice test. Different subgroups of untrained words were used across the 5 runs to avoid the practice effect in both training conditions.

Stimulus presentation and response collection were programmed using Matlab (Mathworks) with Psychtoolbox 3 extensions (<http://www.psychtoolbox.org/>) on an IBM-compatible computer.

2.4. tDCS procedure

Two matched groups of participants received anodal tDCS stimulation either on the LTPC or on the VC at the beginning of Session 1 (day 1) and Session 2 (day 3) (Fig. 1C). The electric current was constant and delivered by a battery-driven stimulator (Multichannel noninvasive wireless tDCS neurostimulator, Starlab, Barcelona, Spain), which was controlled through a Bluetooth signal. It was adjusted to induce cortical

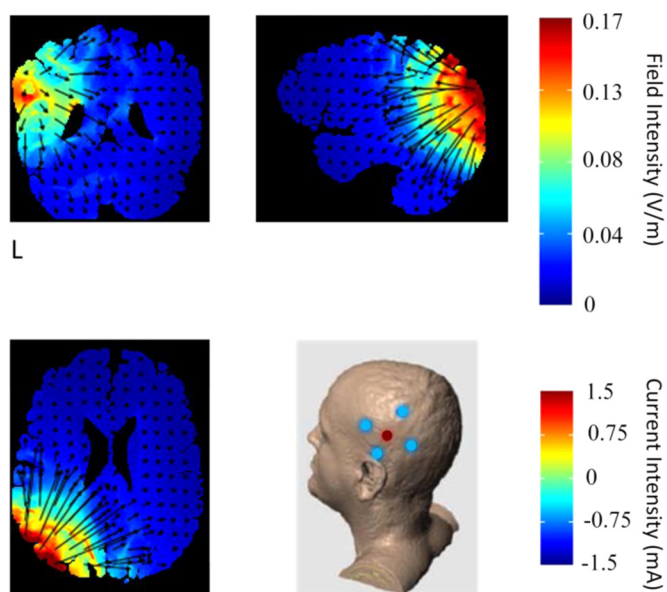


Fig. 2. The electrode locations, current intensity, and field intensity of the HD-tDCS on LTPC.

excitability of the target area without any physiological damage to the participants.

Five disk electrodes (11 mm in diameter) submerged in gel were placed in a 4 × 1 high-definition ring configuration [56]. The locations of the stimulation were determined by the international 10–20 EEG electrode placement system, which has been reported to be reliable and successful [57,58].

For the experimental condition, the stimulation site of LTPC was located halfway between T3 and P3 [59,60], around which were the four return electrodes, CP5, CP1, Pz, and PO7 that each took up 25% of the return current (Fig. 2). For the control condition, the stimulation site of the visual cortex was Oz [61–63], and the return electrodes were PO3, O1, PO4, and O2, with each also taking up 25% of the return current. The visual cortex was chosen as the control site because it was response for the basic visual processing that was not involved in phonological access.

For both conditions, a direct current with an intensity of 1.5 mA was applied for 20 min, and a 30-s fade-in-and-fade-out design was added before and after stimulations to reduce the sensation caused by tDCS. The safety and efficiency of this design was established in previous studies [64].

2.5. Data analysis

Performances of the LTPC and VC groups were compared mainly between the untrained words in the assembled condition and the trained words in the addressed condition. This was because the former could only be read through GPC rules and thus reflected pure assembled phonology, and the latter could only be read through whole-word mapping and reflected pure addressed phonology.

Mixed ANOVAs were used to test the interaction effect between stimulation (LTPC or VC) and training condition (addressed and assembled phonology) on performance on the word choice test (i.e., RT and accuracy). Given the expected differences between trained words (in one condition) and untrained words (in another condition), we would not report those effects (always in favor of trained words) in the Results section. Similarly, given that it is a training study, the main effect of run would be reported only for the initial analysis showing training effect and would be omitted for subsequent results. Instead, analyses focused on the main effect of stimulation and its interactions with condition and run.

Table 2

Correlations between outcomes of addressed and assembled training.

	run 1	run 2	run 3	run 4
TW_AD & TW_AS	.20	.17	.50**	.53**
TW_AD & UW_AS	.23	.30*	.52**	.35*
TW_AS & UW_AS	.61**	.61**	.64**	.52**

Note: TW_AD = trained words in the addressed condition; UW_AS = untrained words in the assembled condition; TW_AS = trained words in the assembled condition.

* $p < .05$.

** $p < .01$.

3. Results

The results showed that our training was effective. At the end of training (i.e., run 4), accuracies on the word choice test for the trained words were greater than 80% in both training conditions for both the LTPC and VC groups, and were about 70% for the untrained words in the assembled condition for both groups, indicating that participants had learned the GPC rules.

3.1. Addressed and assembled learning had distinct cognitive correlates

To substantiate the distinctness of the two routes of phonological access in our paradigm, two analyses were conducted. In the first analysis, we correlated the performances (i.e., accuracy) of the two learning conditions. If assembled and addressed learning involve different processes, the training outcomes should not be highly correlated. As expected, the correlations between performances in the two conditions were low to moderate (Table 2). These correlations will be discussed further in the discussion.

In the second analysis, we attempted to identify differential (as well as common) correlates of the two phonological routes. Table 3 shows the correlations between several measures of reading ability and the training outcomes. Visual-auditory learning and sight word efficiency were significantly correlated with training outcome (accuracies at run 4) for both training conditions (all $r > .42$, all $p < .05$), suggesting the importance of general word learning ability in new language learning in both conditions. In contrast, phonemic decoding efficiency was significantly correlated with untrained words in the assembled condition ($r = .60$, $p < .01$), but not with trained words in the addressed condition ($r = .17$, $p = .44$). Direct comparison of the r 's revealed a significant difference between the two correlations ($z = 1.98$, $p = .02$, one-tailed), supporting the expectation that assembled phonology was specifically affected by phonemic decoding efficiency.

3.2. LTPC stimulation enhanced the learning of assembled phonology

To examine whether tDCS at the LTPC selectively facilitated the learning of assembled phonology, we contrasted the untrained words in the assembled condition and the trained words in the addressed condition. A 2 (stimulation: LTPC, VC) × 2 (training method: addressed, assembled) × 4 (run: 1–4) ANOVA on RT data showed a significant

Table 3

Correlations between reading abilities and outcomes of the training.

	TW_AD	UW_AS
Visual-auditory learning	.42*	.47*
Sight word efficiency	.44*	.43*
Phonemic decoding efficiency	.17	.60**

Note: TW_AD = trained words in the addressed condition; UW_AS = untrained words in the assembled condition.

* $p < .05$.

** $p < .01$.

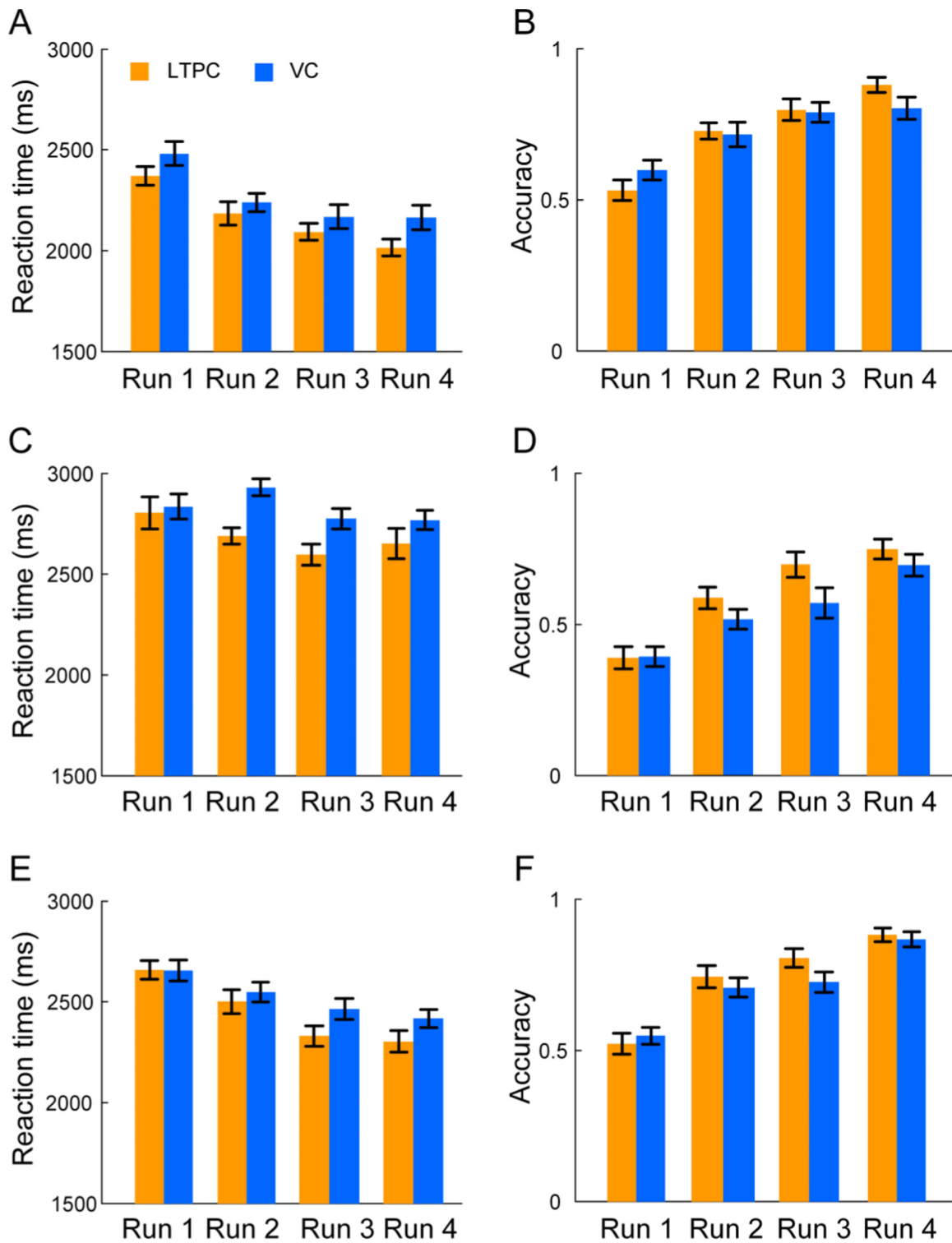


Fig. 3. Performance for the three types of words in the LTPC and VC groups across four runs. (A) Reaction times and (B) accuracy rates for trained words in the addressed condition; (C) Reaction times and (D) accuracy rates for untrained words in the assembled condition; (E) Reaction times and (F) accuracy rates for trained words in the assembled condition. Error bars represent the standard error of the mean.

three-way interaction ($F(3,42) = 3.63, p < .05$). To further explore this three-way interaction, two-way (stimulation by run) ANOVAs were conducted separately by training condition. For the trained words in the addressed condition, we found a significant main effect of run ($F(3,42) = 35.76, p < .001$), but neither a main effect of stimulation ($F(1,44) = 1.61, p = .21$) nor a significant interaction between stimulation and run ($F(3,42) = 1.16, p = .33$). For the untrained words in the assembled

condition, there were significant main effects of stimulation ($F(1,44) = 5.52, p = .02$) and run ($F(3,42) = 3.42, p = .02$), and a significant stimulation by run interaction (quadratic, $F(3, 42) = 6.66, p = .01$). Further paired-sample analysis suggests that the stimulation had significant effects on run 2 ($t(44) = -4.04, p < .001$) and run3 ($t(44) = -2.51, p = .02$), but not on run 1 ($t(44) = -.31, p = .76$) or run 4 ($t(44) = -1.30, p = .20$). These results suggest that LTPC stimulation

specifically enhanced assembled phonology (Fig. 3A and C).

Similar to the results based on RT data, a 2 (stimulation: LTPC, VC) \times 2 (training method: addressed, assembled) \times 4 (run: 1–4) ANOVA on accuracy data showed a marginally significant three-way interaction ($F(3,42) = 1.84, p = .09$). For the trained words in the addressed condition, there was a significant main effect of run ($F(3,42) = 58.99, p < .001$), but neither significant main effect of stimulation ($F(1,44) = .03, p = .86$) nor interaction between stimulation and run ($F(3,42) = 1.25, p = .13$). For the untrained words in the assembled condition, there were a significant main effect of run ($F(3,42) = 68.37, p < .001$), and a marginally significant interaction between stimulation and run ($F(3,42) = 2.54, p = .06$), but no significant main effect of stimulation ($F(1,44) = 1.98, p = .17$). Further paired-sample analysis suggests that the stimulation had significant effects on run 3 ($t(44) = 1.98, p = .05$), but not on other runs (all $p > .25$) (Fig. 3B and D).

3.3. LTPC stimulation enhanced long-term maintenance of assembled phonology

2 (stimulation: LTPC, VC) \times 2 (training method: addressed, assembled) mixed ANOVAs were performed for the RT and accuracy data of the word choice test from Session 3. There were significant main effects of stimulation ($F(1,44) = 5.34, p = .03$) and training method ($F(1,44) = 125.54, p < .001$), and a marginally significant interaction between stimulation and training method on RT ($F(1,44) = 4.69, p = .06$). Simple effect analysis further revealed that the LTPC group outperformed the VC group for the untrained words in the assembled condition ($t(44) = 2.94, p < .01$), but there was no stimulation effect for the trained words in the addressed condition ($t(44) = 1.30, p = .20$) (Fig. 4A). This result suggests that the LTPC stimulation facilitated the long-term maintenance of the newly acquired assembled phonology. For the accuracy data, there were no significant main effects of stimulation ($F(1,44) = 1.77, p = .19$) and training method ($F(1,44) = 2.45, p = .12$), or significant interaction between stimulation and training method ($F(1,44) = .51, p = .48$) (Fig. 4B).

3.4. tDCS effect on the trained words in the assembled condition

Although the trained words in the assembled phonology training condition could not provide unambiguous information due to the possibility of the strategy-shift hypothesis [5,65,66], results from these words were also analyzed for exploratory purposes using a 2 (stimulation: LTPC, VC) \times 4 (run: 1–4) two-way ANOVA. For both dependent measures (the RTs and accuracies of the word choice test), there was a significant main effect of run (all $p < .001$), but neither main effect of

stimulation nor stimulation by run interaction was significant (all $p > .14$) (Fig. 3E and F). Although not statistically significant, the pattern of the results was similar to the untrained words. We also tested stimulation difference for the trained words in the assembled condition in Session 3 and found no stimulation differences for either RT or accuracy data (all $p > .25$) (Fig. 4A and B).

4. Discussion

Using HD-tDCS and an artificial language training paradigm, this study found that anodal stimulation on the LTPC specifically facilitated the test performance of the untrained words in the assembled training condition, but not the trained words in the addressed training condition. These results provide causal evidence for the role of the LTPC in assembled phonology. In addition, the beneficial effect was still present four days after the last stimulation session, indicating that repeated applications of anodal tDCS on LTPC had long-term benefits on assembled phonology.

Our study found clear evidence for the dissociation of assembled phonology and addressed phonology under our training paradigm. First, the outcomes of the two training conditions were only moderately correlated. Second, by calculating the correlations between reading abilities and training results, we found both common and distinct predictors of the two training methods. Visual-auditory learning and sight word efficiency, which reflect general word learning ability, could predict learning performance in both training conditions. In contrast, phonemic decoding efficiency, which reflects word decoding ability [54,67], specifically contributed to learning in assembled phonology.

By combining an artificial language training paradigm and tDCS, the present study had the following strengths. First, the artificial language training paradigm allowed for a strict match of the addressed and assembled training conditions on visual form and phonology, number of repetitions, and overall learning time. Second, the artificial language used in this study included only visual forms and sounds without semantics assigned to the words, which allowed for a comparison of assembled and addressed phonology as pure orthography-to-phonology processes. Third, high-definition tDCS with the stimulation of the visual cortex as a control condition lent strong evidence for a causal role of the stimulated region in the function in question.

Our findings are in line with previous brain stimulation studies that highlighted the role of the LTPC in word learning [41,42,44,68]. It should be noted that the temporoparietal cortex comprises several subregions that are involved in various functions such as attention [60], semantic processing [69], and word decoding [42,70]. However, the low resolution of the conventional tDCS does not allow researchers to

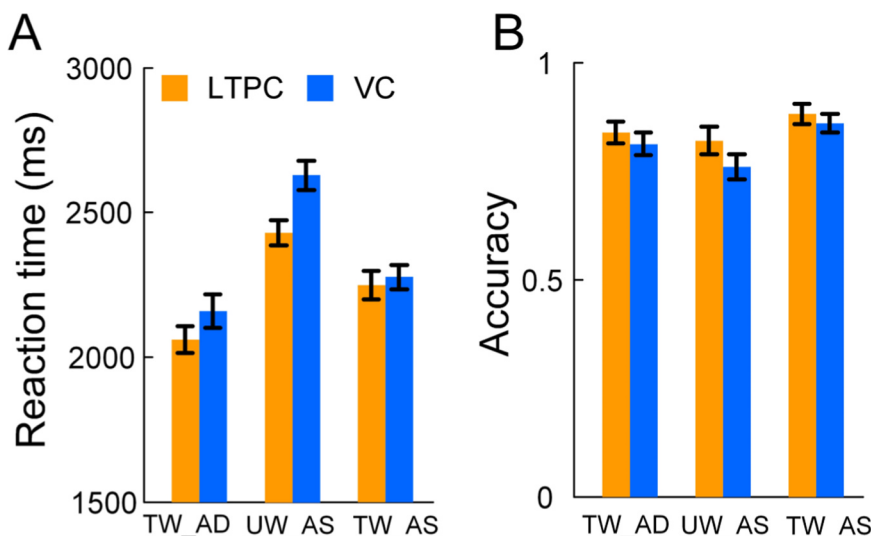


Fig. 4. (A) Reaction times and (B) accuracy rates for the three types of words for the LTPC and VC groups for Session 3. TW_AD = trained words in the addressed condition; UW_AS = untrained words in the assembled condition; TW_AS = trained words in the assembled condition. Error bars represent the standard error of the mean.

separate these functions. Computational modeling studies have suggested that the 4×1 tDCS montage used here could produce more focal stimulation than could the conventional tDCS [45,48,49]. The use of HD-tDCS might have ruled out the potential confounds of tDCS-related general attention or semantic processing.

More importantly, our study revealed that repeated applications of tDCS on the LTPC could have long-term benefits on assembled phonology. This result is in line with previous studies that examined long-term maintenance of tDCS effects for motor skills [71,72], numerical abilities [73], and language abilities [44,70]. For example, a previous study on aphasia rehabilitation found that gains during tDCS were maintained beyond the end of the training period [70]. Previous studies on skill acquisition suggested that repeated stimulation affected protein synthesis [71], which may serve as the underlying neural mechanism of enhanced long-term maintenance of tDCS effects in the present study and even longer maintenance (i.e., several months) of such effects in other domains [71,73].

The stimulation effect revealed by the present study has important implications for clinical and educational interventions. First, our results suggest that anodal tDCS on LTPC might constitute an effective treatment for deep dyslexia and aphasia that suffer similar grapheme-to-phoneme transformation problems. Future studies should directly test the efficacy of anodal tDCS on LTPC in improving reading skills of these clinical groups. Second, our study also suggests a potential way to improve second language learning, particularly for languages with transparent GPC rules. Perhaps such an intervention would reduce the assimilation effect of the native language that tends to hinder second language learning (i.e., Chinese speakers using addressed phonology to learn an alphabetic language) [55,74]. Specifically, previous studies have reported that key regions (i.e., LTPC) for assembled phonology are not involved when reading Chinese [75,76]. One recent study found that Chinese subjects' LTPC (i.e., the left temporal area) was not sufficiently active when reading English [77]. Similarly, it has been found that LTPC (i.e., the left supramarginal gyrus) was less active for Chinese speakers than for English speakers when they used assembled phonology [36]. The results of the present study suggest that anodal tDCS to LTPC may facilitate Chinese speakers' learning of English or other transparent languages.

Our results discussed above revealed a specific effect of LTPC stimulation on untrained assembled words. A similar, but statistically not significant, pattern was found for the trained assembled words. We speculated that with training, assembled words may have undergone the classic shift of reading strategy from assembled phonology to addressed phonology [5,65,66]. In partial support of this speculation, a post hoc analysis found a trend of an increased correlation between trained addressed words and trained assembled words from run 1 ($r = .20$, $p = .17$) to run 4 ($r = .53$, $p < .001$), but a decreased correlation between trained assembled words and untrained assembled words from run 1 ($r = .61$, $p < .001$) to run 4 ($r = .52$, $p < .001$) (Table 2). These results are consistent with one previous fMRI study by our group that showed direct neural evidence of the strategy shift from assembled to addressed phonology during the process of learning to read an artificial language [37].

Several future research directions should be discussed. First, this study used a between-subject design for the stimulation conditions (but a within-subject design for the training conditions) to avoid the practice effect in artificial language learning. Although we matched the two groups of participants carefully, they might still differ in some aspects, which potentially affected the results of this study. Future studies should use larger samples to confirm the findings of this study. Second, the long-term maintenance of the stimulation effect was only assessed after a delay of several days, so future studies should examine this effect with longer delays. Third, future studies should combine HD-tDCS and functional imaging methods to further elucidate the neural mechanisms of the facilitation effect. Finally, although the miniature artificial language could help to clearly dissociate addressed and assembled

phonology, future studies should use natural languages and more intensive training to examine the clinical and educational applications of tDCS.

In conclusion, by combining HD-tDCS and an artificial language training paradigm, the present study revealed a causal role of the left temporoparietal cortex (LTPC) in the learning and long-term maintenance of assembled phonology, but not addressed phonology. These results provide additional evidence for a neural dissociation between these two routes of phonological access, and also have important potential implications for clinical and educational interventions.

Ethical statement

This study was approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University.

Conflict of interest

The authors declare no competing financial interests.

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