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

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ABSTRACT

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. By combining high-definition transcranial direct current stimulation (HD-tDCS) and an artificial language training paradigm, the present study aimed to examine the causal role of LTPC in assembled phonology and tDCS's short- and long-term facilitation effect on reading via assembled phonology. 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. 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, indicating that 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., fylfot) 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 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.

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).

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 ± .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 ± .50, with a