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Reading Proficiency Influences the effects of Transcranial Direct Current Stimulation: Evidence from Selective Modulation of Dorsal and Ventral Pathways of reading in Bilinguals

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Abstract

Introduction: tDCS can modulate reading which is processed by lexical (ventral) and sublexical (dorsal) pathways. Previous research indicates that pathway recruitment in bilinguals depends on a script's orthographic depth and a reader's proficiency with it. The effect of tDCS on each reading pathway has not been investigated in bilinguals. We stimulated the left dorsal and ventral pathways separately in Chinese-English (C-E) bilinguals to understand whether pathway-specific modulation by tDCS is possible and, if so, how it is influenced by orthographic depth and script proficiency.

Methods: A double-blind, sham-controlled, within-subject experiment was designed wherein 16 balanced bilinguals received anodal tDCS in dorsal, ventral and sham sessions. Two tDCS montages of electrode sizes 5 X 5 cm^2 with 1) anode at CP5 and cathode at CZ, and 2) anode at TP7 and cathode at nape of the neck, were applied for stimulating the dorsal and ventral pathways respectively. Bilinguals were asked to read word lists for each language before and after

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[7]Authors' contribution
SB conducted the experiment, performed analyses, and taken the lead in manuscript writing. RK contributed with statistical analyses, and BO contributed to acquiring language proficiency data. RK, BO, KO, JD, MM, BR, and SC were a part of technical discussions and contributed to several revisions during manuscript preparation. BR and SC were in charge of overall direction and planning and contributed to the interpretation of results.

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stimulation. RTs for accurate trials were analysed using linear mixed-effect modelling that included proficiency scores for reading English pseudo-words (PW) and Chinese pinyin.

Results: For both languages, word reading RTs were faster following dorsal pathway stimulation. The dorsal stimulation effect (change in RT) was negatively correlated with pseudoword reading and pinyin proficiency. Stimulation of the ventral pathway decreased RTs only for Chinese reading.

Conclusion: Dorsal and ventral reading pathways can be selectively modulated by tDCS in bilingual readers with dorsal (sub-lexical) pathway stimulation affecting reading in both scripts and ventral (lexical) pathway stimulation selectively affecting Chinese reading. Dorsal pathway tDCS effects are modulated by sub-lexical reading proficiency.

Keywords

transcranial direct current stimulation (tDCS); dorsal and ventral route of reading; Chinese-English bilingual; proficiency

1 Introduction

Transcranial direct current stimulation is a non-invasive brain stimulation technique that involves passing a weak direct current through cortical regions via two or more electrodes placed on the scalp (Nitsche & Paulus, 2000; Priori et al., 1998). tDCS acts by inducing subthreshold changes in resting membrane potential (Stagg & Nitsche, 2011), which in turn can alter the spontaneous firing rate of neurons (Fertonani & Miniussi, 2017). tDCS effects are also driven by activation of the NMDA receptors caused by a decrease in GABAergic tone; and the lasting aftereffect is driven by long term potentiation like plasticity (Friehs & Frings, 2019). tDCS is cost-effective with minimal side effects (Kessler et al., 2012). Previous studies have shown that tDCS can modulate reading behaviour in both healthy (Bhattacharjee et al., 2019a; Boehringer et al., 2013; Flöel et al., 2008; Turkeltaub et al., 2012), as well as reading-impaired individuals (Cancer & Antonietti , 2017; Costanzo et al., 2019; Costanzo, Varuzza, Rossi, Sdoia, Varvara, Oliveri, Giacomo, et al., 2016; Costanzo, Varuzza, Rossi, Sdoia, Varvara, Oliveri, Koch, et al., 2016; Heth & Lavidor, 2015). Thus, in addition to behavioural interventions, the use of neuro-modulation techniques has been considered for remediating reading difficulties (Cancer & Antonietti, 2018).

Successful reading involves using either lexical (word-based), or sub-lexical processes (letter-based), or their combination (Cattinelli et al., 2013; Jobard et al., 2003). In typically reading adults, the reading process is dominated by the left hemisphere and involves two neural pathways - 1) A ventral pathway that has been associated with lexical processing, involving: left middle temporal gyrus, basal temporal area and inferior frontal gyrus (pars triangularis); 2) A dorsal pathway supporting sub-lexical processing involving the: inferior parietal lobule, superior temporal gyrus and inferior frontal gyrus (pars opercularis); (Cattinelli et al., 2013; Jobard et al., 2003; Perfetti et al., 2013). Lexical reading processes involve the retrieval from long-term memory of previously stored meanings and pronunciations of whole words. Sub-lexical reading processes, in contrast, involve assembling pronunciations based on sub-word units (e.g., letters). Words with unpredictable pronunciations (irregular words; e.g., YACHT) must be processed lexically, while unfamiliar words (or pseudo-words; e.g., FLOPE) must be processed sub-lexically. Thus, one strategy for furthering our understanding of the neural bases of reading would be to selectively stimulate each of the pathways and investigate the effects on reading efficacy, something which has not been attempted in previous studies.

To investigate the effect of selective stimulation of dorsal and ventral pathways on reading efficacy two aspects are crucial - (1) targeted stimulation of dorsal and ventral pathways in a manner that stimulation of one pathway does not influence the other; and (2) use of reading tasks that primarily recruit either lexical (ventral) or the sub-lexical (dorsal) processing. The first objective is achieved through a computational framework named *S*ystematic *A*pproach for *t*DCS *A*nalysis (SATA). SATA has been shown to identify optimal montage for dorsal and ventral pathways of reading (Bhattacharjee et al., 2019b). Specifically, SATA has demonstrated that the two montages of electrode size 5 X 5 cm^2 with 1) anode at CP5 and cathode at CZ, and 2) anode at TP7 and cathode at the nape of the neck, targets the dorsal and ventral pathway, respectively (Bhattacharjee et al., 2019b), (for details also refer to the Methods section). The second objective can be achieved by investigating the effect of lexical and sub-lexical pathway stimulation on the real word (RW) and pseudo-word (PW) reading. Using RW and PW reading tasks in monolinguals, neuroimaging studies have found selective activation in lexical (ventral) and sub-lexical (dorsal) pathways, respectively, due to the differences in the degree to which each task relies on lexical and sub-lexical processing (Danelli et al., 2015; Roux et al., 2012; Savill et al., 2019; Sliwinska et al., 2015; Wilson et al., 2007). However, studies involving tDCS stimulation of the posterior temporal cortex in monolinguals found no changes in PW reading efficacy, although RW reading was effectively modulated, (Cancer & Antonietti, 2018; Turkeltaub et al., 2012). One reason for such findings could be that the underlying regions that are involved in sub-lexical processing during PW reading were not explicitly targeted.

In the present study, we take the approach of investigating the effect of selective stimulation of the pathways involved in lexical (ventral) and sub-lexical (dorsal) processing, considering only real word (RW) reading. To evaluate the contribution of the two pathways, we use bilingual readers of two orthographies (Chinese and English) that are known to make different demands on lexical and sub-lexical reading processes. In this way, bilinguals provide a unique opportunity to test the effect of tDCS on the two reading pathways in real word reading within the same person. Based on the different cognitive demands of the two orthographies, it is expected that they will primarily recruit either the lexical (English) or the sub-lexical (Chinese) processing. Additionally, it is also important to note that studies have found that the utilization of these reading pathways in bilinguals also depends on the relative proficiency with the script (Abutalebi, 2008; Indefrey, 2006; Stowe & Sabourin, 2005), a factor that we discuss in Section 1.2. Although issues concerning the recruitment of lexical and sub-lexical pathways in reading can be examined in monolinguals, bilingual readers provide unique opportunities for such investigations.

1.1 Influence of orthographic depth on the effect of tDCS applied to dorsal and ventral pathways of reading

Scripts differ in terms of their orthographic depth (or transparency), which refers to the degree to which word pronunciations are predictable from the written form. Thus, for example, English has a more transparent (less deep) script than Chinese, while Spanish has a more transparent script than English. While lexical and sub-lexical processes are recruited for all scripts, less transparent scripts rely more on lexical processes while reading in more transparent scripts can be accomplished with greater reliance on sub-lexical processes (Buetler et al., 2015; Buetler et al., 2014). For example, English uses an alphabetic script in which written symbols (letters), represent consonants or vowels, are arranged in a string. The mapping of letters to sounds is more or less predictable and, therefore, pronunciations can be generated based on "assembled phonology" such that the individual phonemes within a word are combined to pronounce the word. This type of process takes place through the sub-lexical pathway (Reynolds & Besner, 2005; Vitevitch, 2003; Zhou et al., 2010). On the other hand, lexical processing in English is required to read irregular words, where the pronunciation of word is not predictable from its spelling (Altenberg & Cairns, 1983; Buetler et al., 2014; Kovelman et al., 2008). Similarly, Chinese has a logographic script with characters representing morphemes (rather than individual sounds), each of which can be only be read as a whole word. Thus in Chinese, assembled phonology cannot be applied (Koda et al., 2014). In fact, Chinese characters are largely read through addressed phonology (via the lexical pathway) where a character's meaning is retrieved as the basis for retrieving the associated phonology (Perfetti et al., 2013). Cheng, 1992; Nelson et al., 2009; Yan et al., 2012). However, many studies have also demonstrated the existence of sub-lexical processing in Chinese reading (Booth et al., 2006; Dang et al., 2019; Wu et al., 2012). In fact, a recent study by Dang et al., claimed that the phonetic and semantic components of Chinese characters need to interact for successful mapping from orthography to phonology (Dang et al., 2019). Thus, while the English and Chinese reading may differentially rely on sub-lexical and lexical processing respectively, sub-lexical processing is also used for reading Chinese (Bakhtiari et al., 2014; Tan et al., 2005) and, likewise, lexical processing is also needed for English reading (Nelson et al., 2009).

Neuroimaging studies have provided evidence that dorsal (sub-lexical) and ventral (lexical) pathways might be activated differentially in bilinguals, reflecting the different processing demands of the two languages (for example, in Hindi-English bilinguals (Cherodath & Singh, 2015; Das et al., 2011); and Spanish-English bilinguals (Jamal et al., 2012; Meschyan & Hernandez, 2006). Investigating the effect of orthographic depth in Chinese-English (C-E) bilinguals, a study found that during reading English words compared to a control condition (fixation) (Ping, 2003), there was increased activity in the dorsal pathway regions like the left inferior parietal regions (BA 40, 39), left superior temporal gyrus, and left inferior frontal gyrus (BA 45,44). The study also found that, for reading in Chinese (Ping, 2003), there was greater activation in the ventral pathway consisting of the left middle frontal gyrus (BA 9, 46), and parts of the superior and middle temporal gyri (BA 21, and 22). This indicates that in reading English, C-E bilinguals seem to rely more on the sub-lexical pathway and in reading Chinese they might rely on the lexical pathway. Although such neuroimaging activation within dorsal and ventral pathways seems to be consistent with the orthographic properties of the two languages of C-E bilinguals, many questions remain regarding the roles of these pathways. In this context, tDCS can provide a useful tool since stimulating a pathway and observing the change in the behaviour can provide the basis for stronger inferences about the neural processing strategy. Therefore, our study proposes to use tDCS with C-E bilinguals to further our understanding of the influence of orthographic depth on the recruitment of dorsal and ventral pathways for reading.

As indicated above, for English, a straightforward approach to evaluating the role of ventral and dorsal pathways in reading is to examine RW and PW reading, which are, respectively, clearly established measures of lexical and sub-lexical processing. In contrast, measures for evaluating lexical sub-lexical processing and pathway recruitment in Chinese are not as straightforward. This is because the logographic Chinese characters primarily represent the meaning of a morpheme, and their relationship with the pronunciation of the morpheme is not straight forward (Pine et al., 2003) and, therefore, PW reading in Chinese is not a viable measure of sub-lexical reading. In this regard it is important to note that pinyin is the use of the Roman alphabet in teaching reading and spelling Chinese in Singapore and is currently frequently used during texting in electronic media. Chen et al., (2002) reported a clear distinction between activation of the ventral and dorsal pathways for reading Chinese characters and it's pinyin, respectively. One possibility is that higher proficiency and regular usage of pinyin by C-E bilinguals might promote the recruitment of sub-lexical processing during the reading of Chinese characters themselves. If that were the case, then proficiency in reading high frequency Chinese characters (CCR) and pinyin reading could serve as measures of lexical and sub-lexical processing, respectively. Moreover, if pinyin proficiency shifts the dependence of Chinese character reading towards the sub-lexical system, then investigating the relation of pinyin proficiency with pathway recruitment during Chinese reading could be of general interest since pinyin proficiency might be a confound in studies of C-E bilinguals. For these reasons, in the present study we will examine the role of pinyin proficiency on tDCS effects.

1.2 Influence of language proficiency on tDCS stimulation of the dorsal and ventral pathways of reading.

It is common in bilingual societies that one of the languages is used more often than the other. A review of studies has concluded that similar regions in the brain of a bilingual are employed for processing the two spoken languages; however the utilization strategy depends on the proficiency of a language (Stowe & Sabourin, 2005). In fact, higher proficiency and dialy usage of one language in bilinguals might lead to overuse of one system leaving another system underused (Stowe & Sabourin, 2005). Previous studies also reported increased activation and recruitment of additional language areas for processing the less proficient language compared to the native language in early bilinguals (Hernandez, 2009; Perani et al., 2003). Hence, it is plausible that proficiency profiles in bilinguals might influence how recruitment of reading pathways (dorsal and ventral) would be affected by tDCS.

The present study includes early Chinese-English bilinguals (participants who acquired both languages < 7 years of age) and who, therefore, were expected to have similar proficiency levels in both languages. However, in addition to age of acquisition, language use/exposure is a relevant variable. Frequent usage of a language in day to day practice is linked with an increase in the level of lexical processing and, additionally, language exposure has been found to affect the pattern of neural activation in the lexical regions in bilinguals, even if both languages were acquired early with an equivalent level of proficiency (Perani et al., 2003). In this regard, it is critical to note the typically higher exposure to English (compared to Chinese) in Singapore. English is often the language that is extensively used in day to day conversation, and sometimes it is the primary language for communication within the family. Even if Singaporeans are exposed to Chinese at home, it is often only in the spoken form and formal training with characters reading and writing typically begins at only at preschool level. The usage differences between the two language might affect pathway recruitment in reading. For example, routine and extensive use of English language by Singaporean C-E bilinguals might lead to especially strong recruitment of the lexical pathway compared to sub-lexical pathway for English word reading. In contrast, given the relatively lower proficiency and exposure to Chinese, extra processing resources might be needed for Chinese word reading, resulting in recruitment of both lexical and sub-lexical pathways.

Relevant to the issue of proficiency are findings from previous studies with healthy participants that have shown that tDCS effectively modulates reading behaviour only in below average readers (Cancer & Antonietti, 2018; Turkeltaub et al., 2012). For example, Turkeltaub et al. (2012), found that only those participants who scored below average in reading tasks during sham stimulation (12 out of 20 healthy readers) exhibited significant effects of tDCS modulation (Turkeltaub et al., 2012). Thus, it is possible that if an individual is less proficient in utilizing a particular process (lexical or sub-lexical), tDCS would show stronger stimulation effects, and vice versa.

1.3 Gender related differences in tDCS effects

Gender differences in tDCS research is emerging as a topic of interest. Adenzato et al., (2017) found that anodal tDCS enhanced the performance in females, but not in males. Another study found differential improvement in performance of verbal working memory between females and males, following tDCS (Meiron and Lavidor, 2013). Similarly, multiple studies reported that the observed tDCS induced augmentation of cognitive behaviour were gender dependent (Gao et al., 2018; Keshvari et al., 2013; Yang et al., 2018; Bertossi et al., 2017; Wang et al., 2019). Recently, a computational study reported gender related differences in the tDCS induced peak intensity of current at a target region of interest in the cortex. They suggested such differences could be caused by gender related anatomical differences like grey matter, white matter and CSF percentage volumes (Thomas et al., 2019). To our knowledge, the effect of gender on tDCS studies of (bilingual) reading is not known. Therefore, we will consider gender related differences in the present study.

1.4 The current study

The aim of the study was to investigate the effects on English and Chinese word reading behaviour of tDCS applied to left dorsal and ventral reading pathways in C-E bilinguals. Two important questions were addressed with C-E bilinguals. (1) Does the orthographic depth of a language influence tDCS induced enhancement of reading efficacy following selective stimulation of dorsal and ventral pathways? (2) Is tDCS induced enhancement of reading efficacy influenced by language-specific proficiencies in using lexical and sub-lexical processing of reading? To achieve this aim, we used the montages described by Bhattacharjee et al., (2019b) (for details refer to Methods section) to investigate the effect of stimulation on reading of English and Chinese word lists administered separately before and after stimulation.

To address the first question, we used the contrast of languages (English vs. Chinese) to investigate the effect of orthographic depth in the recruitment of the ventral and dorsal pathways of reading in C-E bilinguals. If orthographic depth is relevant, we hypothesized that English reading would be enhanced by dorsal pathway stimulation, and Chinese reading would be enhanced by ventral pathway stimulation. Alternatively, if depth is not especially relevant then both the languages would show enhancement following stimulation of both the dorsal and ventral pathways.

The second question concerns the effect of proficiency on pathway recruitment and tDCS effects. For this study, we recruited early bilinguals, who, we expected to have comparable proficiency levels in both the language. However, the relative difference in exposure and usage of each language in the Singaporean context resulted in proficiency differences, such that, for our participant group, we found higher self-rated proficiency in English reading and writing than in Chinese. In terms of pathway recruitment in word reading we might expect the higher English word reading proficiency to increase the tendency to recruit the lexical pathway. On the other hand, the lower proficiency in Chinese reading and writing might be expected to result in recruitment of both the lexical and sub-lexical pathways to compensate for the lower proficiency. These proficiency differences would be expected to have consequences for the effect of tDCS stimulation given previous findings that tDCS are larger with lower proficiency (Cancer & Antonietti, 2018; Turkeltaub et al., 2012; Younger et al., 2016). Thus, if language proficiency is relevant for pathway recruitment, we might expect that English reading would benefit from stimulation of the (less-utilized) dorsal pathway, whereas Chinese reading would benefit following stimulation of both dorsal and ventral pathways.

To more specifically evaluate the role of proficiency we evaluated whether individual differences in behavioral script-specific lexical and sub-lexical processing scores predict the effects of dorsal and ventral pathway tDCS effects in each language. For English, we used PW and RW reading scores to index sub-lexical and lexical processing efficiency, whereas for Chinese, we use pinyin and character reading scores for this purpose. If these variables are relevant, we hypothesize that lower scores in sub-lexical and lexical reading will be associated with stronger tDCS effects in both the languages following stimulation to the ventral and dorsal pathways respectively.

In sum, this investigation uses selective tDCS applied to dorsal (sub-lexical) and ventral (lexical) reading pathways in Chinese-English bilinguals. This approach allows for furthering our understanding of the roles of orthographic depth and proficiency on the recruitment of these fundamental reading pathways.

2 Methods

2.1 Participants

Subjects were invited for participation through advertisements and emails. They were asked to participate in an online questionnaire to self-rate their linguistic proficiency (on a scale of 1 to 5) and respond to questions regarding the age of acquisition, proportion of daily usage, duration of formal training for each language, etc. Subsequently, only those participants who acquired both the languages before seven years of age were invited for a behavioural session that measured their proficiency in each language using standardized tests (for details refer to section 2.3). 54 C-E bilinguals were brought in for language proficiency testing, out of which only 18 participants with fluent reading capability in both the languages (for details refer to section 2.3) were recruited for the tDCS experiment. These volunteers were further screened for eligibility to participate in tDCS session through an online questionnaire. None of the participants had reading difficulties, neurological or psychiatric illness, history of head trauma, personal or family history of epilepsy, any prescription of psychiatric medications. Pregnant and breastfeeding women were excluded from the study. Participants with scalp abrasions or skin disease inspected on the day of the study were excluded (although none for the current study) to minimize scalp burn risks. All study protocols were reviewed and approved for ethics by the Institutional Review Board at Nanyang Technological University.

2.2 The experimental design

The tDCS experiment was conducted in 3 separate sessions, with a gap of at least 1 day between sessions. Recruited participants were informed of the procedures and gave written consent to participate. Two montages of electrode sizes 5 X 5 cm^2 with 1) anode at CP5 and cathode at CZ, and 2) anode at TP7 and cathode at nape of the neck, were used to target the dorsal and ventral pathway, respectively (Bhattacharjee et al., 2019b) (for details also refer to the methods section 2.5). In each session, the participants were asked to read one rapid naming task (RNT) list in English and one in Chinese before the tDCS stimulation started and then separate but equivalent RNT lists immediately after the tDCS stimulation ended (for details of the RNT task, refer to Task Preparation Section 2.3). Each participant received two active stimulation sessions (actual stimulation) and 1 control/sham session. We adopted a pre and post design (offline tDCS experiment) so that a baseline reading could be obtained during each of the three sessions which were conducted on three separate days. We did so to facilitate the comparison of tDCS-induced effects (pre vs. post-stimulation reading performance) between the active and sham conditions using baseline scores obtained on each day (pre-stimulation performance).

2mA current was delivered through a Neuroconn DC stimulator with either the dorsal or ventral pathway montage during active stimulation; electrodes in saline soaked sponges (5 × 5 cm^2) were placed on the scalp with the help of a rubber belt. The active stimulation lasted for 20 minutes, during which the current was ramped up at the beginning for 30 seconds and ramped down at the end for 29 seconds. In contrast, the current in the sham condition was ramped up for the initial 30 seconds, with no further stimulation before it was ramped down in the last 29 seconds. The electrode positions were maintained at the dorsal montage position for the sham condition. During stimulation, participants were asked to watch visuals of an aquarium (on a desktop monitor) so that a similar state of mind could be maintained during stimulation within and across participants. The participants were asked a few aquarium related questions at the end of each session to ensure that they were attentive (e.g., did not fall asleep) during the stimulation. Since offline tDCS effects are driven by neurotransmitter release within the targeted pathway (Friehs & Frings, 2019), we chose a task unrelated to reading to avoid interference with the underlying mechanisms of interest. Three parameters were randomised across sessions for each participant (1) the order of the 6 equivalent RNT lists, (2) the order of the language (English-Chinese or Chinese-English), and (3) the tDCS condition (dorsal active/ventral active/ sham). The experiment was double-blinded such that neither the participant nor the experimenter was aware of the type of stimulation (active/sham) that the participant received. The blinding was executed via pre-set numerical codes for active and sham stimulation in the Neuroconn machine. After the experiment, each participant was asked to rate the tolerability of the procedure on a scale of 1 (mild) to 5 (severe) for common side effects (i.e., headache, neck pain, scalp pain, tingling, itching, burning sensation, skin redness, sleepiness, trouble concentrating, acute mood changes, and others). Following this, we evaluated if we had successfully blinded the participants, by asking them to report the stimulation condition they thought they received (i.e., active/”real”, sham/”fake”, or “I don't know”). The experiment design and the timeline of each tDCS session is shown in Figure 1.

2.3 Preparation of rapid naming tasks for the main experiment

Six equivalent lists of 50 written words for a rapid naming task (RNT) were prepared for each language (English and Chinese) for use in the three stimulation sessions. 6 equivalent RNTs were required for each language because one version was presented before and after three stimulation conditions (3×2, a total of 6 RNTs): dorsal, ventral, and sham. Equivalent lists were constructed to minimize practice effects within and across sessions. To prepare these lists, 300 unique words were selected from psycholinguistic corpora such as English Lexicon Project (Balota et al., 2007) for English and SUBTLEX-CH (Cai & Brysbaert, 2010) for Chinese words. These words were divided into six lists by matching the list-wise psycholinguistic characteristics. Words of medium frequency were selected to ensure that words would be of sufficient familiarity to participants and yet there would be room for improvement in their response times following tDCS.

English words were matched for frequency, length, number of phonemes, number of syllables, number of morphemes, part of speech, phonological neighbours, orthographic neighbours, average bigram frequency, naming reaction time and accuracies, regularity/irregularity, age of acquisition, concreteness, imageability, consistency/inconsistency. Specific psycholinguistic variables not available from ELP were supplemented from three psycholinguistic databases: (1) MRC psycholinguistic database (Coltheart, 1981) (2) Language R database (Baayen, 2013) and (4) A paper by Berndt et al., for regularity/irregularity assessment (Berndt et al., 1987). Chinese words were matched on length, frequency, phonological consistency, phonological Regularity, position of phonetic radical, structure type, tone, dominant part of speech, number of strokes, number of phonemes, number of radicals, concreteness, and imageability, accuracy in lexical decision, reaction time in lexical decision. Specific psycholinguistic variables not available from SUBTLEX-CH were supplemented by four corpuses: (1) Corpus by Shu et al., (2003) (2) Online Chinese dictionary (Chinese dictionary—Google Search) (3) Chinese single-character word database (Liu et al., 2007) and (4) Corpus by Sze et al., (2014),. Each variable was evaluated with a one-way ANOVA to establish that the six lists were not significantly different from each other ($p > 0.05$)

The comparability of the RNT lists was also evaluated empirically by measuring reading times and accuracy with 33 C-E bilinguals who did not participate in the tDCS experiment. The RNTs were presented to participants on a computer screen via E-prime software, where each word was presented for 2000ms and appeared sequentially on a white screen (Figure 2). The time between the onset of a stimulus and verbal responses were recorded through voice key as RTs and audio clip. The audio clips were used later to determine the accuracy (ACC) for each word. The ACCs for English words were scored according to Standard British, American English, and that were acceptable forms of local Colloquial Singapore English. For Chinese characters, the ACC was marked as 1 when both the character pronunciation and tone are correct and was marked as 0.5 if only the character pronunciation was correct. Each participant was asked to come for a session and perform 12 RNTs (6 in each language) with 1 minute rest after each RNT and 3 minutes between the languages. The order of languages and RNTs were randomised and counterbalanced across participants. RTs and ACCs measures were tested for differences across RNTs within each language, using one-way repeated measure ANOVAs. Non-significant ($p > 0.05$) differences in RT and ACCs increased confidence that the six RNTs within each language were equivalent to each other.

2.4 Measurement of language exposure and proficiencies

From the language questionnaire, we evaluated their self-rated proficiency scores, the proportion of daily usage, and years of formal training in each language. Following this, we asked the participants to come for a session of behavioral tests as follows.

1) Testing the fluency in both the languages: To ascertain that each participant could fluently read in both the languages (bilinguals), we administered two tests: British Ability Scales, Third Edition, BAS3 (Elliot & Smith, 2011), and Chinese character reading (CCR). The BAS-3 Word Reading (Form A) measured the basic reading ability in English. It required participants to read aloud a list of words ($n = 40$) presented on a stimulus card. They were directed to read the items from left to right in a sequential manner. Chinese word reading proficiency was assessed with a character reading (CCR) task that was derived from a corpus of instruction materials from primary schools in Singapore. Simplified high-frequency characters were presented in 3 sets of 25 single-character words, and items were introduced in order of character frequency. A correctly pronounced word received a score of one, and only the correct responses accounted for the total score. For the tDCS experiment, we selected bilinguals (18 out of 54) who could fluently perform the word reading tasks in both the languages as determined by scores equal to or greater than 75% in both the BAS3 reading and CCR tasks.

2) Testing the lexical and sub-lexical proficiencies in both the languages: In English, real words (RW) and pseudo-words (PW) were administered using the Castles & Coltheart2 test (Castles et al., 2009) to measure the lexical and sub-lexical processing capacity. The stimuli were presented in random order with E-Prime (Schneider et al., 2002). Naming accuracies (ACC) and response times (RT) were recorded, the latter as voice onset time with a voice key linked to E-prime. Similarly, for Chinese, the CCR scores obtained above were taken as a measure of lexical proficiency. The sub-lexical processing was evaluated with a pinyin written picture naming task. Participants were asked to write down the pinyin word corresponding to 24-line drawings of objects.

2.5 Montage location for the tDCS experiment

Several previous studies did not find a significant effect of tDCS on reading and subskills of reading in healthy adults (Westwood et al., 2017; Younger et al., 2016), which could have been due to inadequacies in montage selection (Bhattacharjee et al., 2019a; Cancer & Antonietti, 2018). Thus, for this study, multiple conventional montages were compared, and the appropriate montages for dorsal and ventral pathways were decided through a computational method called SATA, which was developed in house (for details, refer to Bhattacharjee et al., 2019b). Here we provide only a brief description.

Conventional montage selection involves the use of toolboxes like COMETS2 (Jung et al., 2013) or ROAST (Huang et al., 2018), that perform a computational simulation to predict the spread of current across the cortex. Figs 3 (A) and (B) show the typical output for cortical current spread as simulated through ROAST, for two conventionally applied montages for reading: 1) anode at CP5 and cathode at CZ (Sparing et al., 2008); and 2) anode at TP7 and cathode TP8 (Costanzo, et al., 2016a,b). However, the conventional output from COMETS2 has limited information regarding the total amount of current that will stimulate the target brain region (e.g., inferior parietal lobe or inferior temporal gyrus). Moreover, it is difficult to measure the extent of overlap in the spread of current, for a pair of dorsal and ventral pathway montages. Our in-house software SATA (available at https://doi.org/10.21979/DMWPZK) and i-SATA(available at https://doi.org/10.21979/N9/5W3RIM) developed in Matlab, post-processes the output information obtained from conventional software like COMETS or ROAST (Bhattacharjee et al., 2019b; Kashyap et al., 2020). The current density values from montages simulated in COMETS (Jung et al., 2013) and ROAST (Huang et al., 2019) are compared based on three characteristics: (1) Average magnitude of current density (MCD) received by each cortical lobe of the brain, (2) Coordinates with high MCD in each cortical area within the lobe, and (3) Number of overlapping coordinates between any two montages (for details refer, Bhattacharjee et al., 2019b). An appropriate montage will have the highest average MCD in the desired cortical lobe, and highest MCD the in the targeted cortical area within the lobe. Additionally, there should be minimal overlap in the spread of current for a pair of montages, thereby ensuring that the targeted regions in each reading pathway is selectively stimulated.

SATA analysis identified appropriate montages with (1) anode at CP5 and cathode at Cz for dorsal pathway, and (2) anode at TP7 and cathode at nape-of-neck for ventral pathway, with electrode sizes 5 × 5 cm^2 and total current intensity of 2mA (Fig 4A and D). With these montages, there was a max average MCD per lobe at the left parietal lobe for dorsal pathway montage (Fig 4B) and at the left temporal lobe for ventral pathway montage (Fig 4E). These montages also exhibited maximum intensity of current calculated through MCD in the supramarginal gyrus (Fig 4C) and middle/inferior temporal gyrus (Fig 4F) targeting dorsal and ventral pathways, respectively. After analysing multiple pairs of montages, we found this pair of montages to have the least spatial overlap in terms of current spread (Fig 4H).

2.6 Data Analysis

For the reading RTs collected during the 3 tDCS sessions, the RTs of incorrect responses were discarded, and the RTs of correct responses in each language were retained for analysis. The RTS were log-transformed and evaluated separately for each language using a linear mixed-effects model (LMEM). LMEM's are sensitive to small sample sizes and individual variation and takes into account item variance (Wiley & Rapp, 2019). Four types of analyses were performed, which are described as follows.

(1) Analysing the effect of Orthographic depth: Two models (one for each language) were evaluated to determine the effects of orthographic depth, In each, there were three fixed factors: (1) type of tDCS stimulation (dorsal, ventral and sham), (2) time (pre and post-stimulation), and (3) gender (male and female). With sham as the neutral condition, there were two main comparisons: dorsal versus sham stimulation, and ventral versus sham stimulation An interaction of items (each word) and subjects was included as a random factor to account for the variability of items within an individual and across individuals ('crossed random effect'- that accounts for inter-individual differences). We adopted the "maximal structure" for random factors as recommended by Barr et al., (Barr et al., 2013), which includes random intercepts and slopes by both items and participants for each of the fixed-effects. For convenience, we will refer to these LMEM's as LMEM_English and LMEM_Chinese. The analysis was performed using Matlab, and the result was considered significant at $p < 0.05$ FWE-corrected (family-wise error corrected for multiple comparisons).

(2) Analysing the effect of Proficiency: Since a key objective was to investigate the effect of proficiency measures on tDCS stimulation, in a second set of analyses, each script-specific proficiency measure was added to the original LMEM's as a covariate. Specifically, for English, this second set of LMEM's included as fixed factors RW and PW reading ACC scores (percent accuracy). In contrast, CCR and pinyin scores (percent accuracy) were included in the analysis of Chinese reading (see Tables 3S and 4S). We will refer to these LMEM's as LMEM_English_RW, LMEM_English_PW, LMEM_Chinese_CCR, and LMEM_Chinese_pinyin. As described earlier, these reading proficiency scores of participants were obtained independently of the tDCS experiment. Additional cross analyses were performed to predict English reading with Chinese proficiency scores and vice versa. We will refer to these cross-language LME's as LMEM_English_CCR, LMEM_English_pinyin, LMEM_Chinese_RW, and LMEM_Chinese_PW. Model fits for models with and without the inclusion of proficiency scores were examined statistically by comparing the model fit statistics of maximum likelihood ratios.

(3) Post-hoc analyses for proficiency: Post-hoc analyses were performed to understand the three-way interaction between type of stimulation (dorsal, ventral, sham), time (i.e., pre and post-stimulation), and proficiency scores (Chinese, English). In these analyses, the change in RT (post - pre stimulation) for each of the three stimulation conditions was predicted by the RW or PW (Chinese or English) proficiency scores, using linear regression.

(4) Analysing the gender related differences in tDCS effect: To analyse the interaction between gender and stimulation effects, the change in RT values (post - pre) for the two languages were combined. LME was used to evaluate the combined data, with the type of stimulation (dorsal/ventral/sham), and gender (male/female) as fixed factors, language (English/Chinese) as covariates, and items and participants as random factors.

3 Results

3.1 Language Exposure and Proficiency measurements

Language exposure and proficiency results for the C-E bilingual participants are shown in Figure 5. Figure 5A shows that participants had a significantly higher proportion of daily usage for the English language compared to Chinese (t=3.22, p=0.001). They also had a higher duration of formal training in English compared to Chinese (t=2.24, p=0.01), as seen in Figure 5(B). The plot for self-rated proficiency scores in Figure 5C and D shows that the participants had comparatively higher proficiencies in English reading (t=2.51, p=0.008) and writing (t=2.63, p=0.006), compared to Chinese.

English RW accuracies (93.5% ± 4.6) were higher and less variable compared to PW scores (82.8% ± 11.3), and they were significantly different from one another (p < 0.001, Figure 5E). In Chinese the CCR (93.2% ± 5.1) and pinyin scores (88.75% ± 10.2) were not significantly different from one another (P > 0.05, Figure 5F).

3.2 tDCS experiment

18 Chinese-English right-handed, bilingual speakers (8 males and 10 females, mean age = 24.10 ± 4.9 SD) were recruited for this study, and 16 (8 females) were retained for analyses as two participants did not complete all the sessions. All participants tolerated the tDCS protocol and were generally compliant throughout the experiment. Tingling was the most commonly reported side effect (93.75% dorsal active; 100% ventral active; 87% sham) followed by itching (56.25% dorsal active; 77.5% ventral active; 35% sham), burning sensation (0.06% dorsal active; 12.5% ventral active; 0.06% sham), and sleepiness (25% dorsal active; 12.5% ventral active; 58.75% sham), majority of which were mild in nature. Blinding was adequate since there were no significant group differences between individuals stating their stimulation condition ($\chi 2 = 0.889$, p = .279). The LMEM results for RTs and in both English and Chinese are reported in Table 1-4S. The accuracy analyses did not show any significant effects in either Chinese or English LMEM's because participants named most of the words accurately (99.1% in English and 85% in Chinese).

(1) Effect of difference in Orthographic depth of the languages: The English_LME evaluating RTs showed the main effect of dorsal stimulation to be significantly different from sham stimulation (β_1=0.3, p=0.04), whereas the main effect of ventral stimulation was not significantly different from sham (β_1=0.14, p=0.12). Furthermore, it was found that the interaction effect of time (pre vs. post) for dorsal stimulation was significantly different compared to sham (β_1=−0.615, p=1.26E-07), while this was not the case for ventral stimulation (β_1=0.19, p=0.15, refer Table 1S). Estimation of marginal means showed that the mean and standard deviation (std) of RTs significantly (p =0.002) decreased in post-stimulation (612.27 ± 27.87) compared to pre-stimulation (690.6 ± 27.87) of the dorsal pathway. Such significant changes in RTs were not found following ventral and sham stimulation ($p > 0.05$). It was also found that the change in RTs (post vs. pre) for dorsal stimulation was affected by the gender of an individual (β_1=0.27, p=0.02). An additional analysis was performed to understand this three-way interaction for the type of stimulation, time, and gender, which will be discussed separately in the later section. For ease of visualization, we have plotted the distribution of the average values of the trials (raw data) of each participant for the English language, in Figure 6A.

Similarly, the RTs in Chinese reading were analyzed with the Chinese_LME (see Table 2S). The analysis found that the interaction effect of time (post vs. pre) and type of stimulation was significantly different for both ventral (β_1=−0.25, p=0.04), and dorsal (β_1=−0.33, p= 0.01) stimulation compared to sham. The estimation of marginal means showed that RTs measured post-stimulation (665.64 ± 25.22) significantly decreased from pre-stimulation (713.91 ± 25.22) in the dorsal pathway. Similarly, RTs measured post-stimulation (648.25 ± 39.66) was significantly reduced from pre-stimulation (719.45 ± 39.66) in the ventral pathway. A significant difference in a post vs. pre-stimulation condition was not seen for sham stimulation ($p > 0.05$). In the same model, it was also found that the modulation of dorsal (β_1=0.35, p=0.001) and ventral (β_1=0.24, p=0.04) stimulation was affected by the gender of the participant (as demonstrated by the three-way interaction of the type of stimulation, time, and gender). Table S2 (supplement) shows the formula and the result of LME applied to Chinese reading. For ease of visualization, we have plotted the distribution of the average values of the trials (raw data) of each participant for the Chinese language, in Figure 6B.

(2) Effect of the difference in Proficiencies of the languages: We evaluated separate LMEM’s which had the sub-lexical (PW and pinyin) and lexical (RW and CCR) proficiency scores as covariates for both the languages. The LME re-analyses that included word reading proficiency scores (LMEM_English_RW and LMEM_Chinese_CCR) did not result in any significant differences compared to the original LMEM's (English_LMEM and Chinese_LMEM), and therefore will not be discussed further.

When PW reading proficiency was included in the analysis of the English data, the significant effect of tDCS on reading times following dorsal stimulation in the English_LME (Table 1S) was no longer significant (β_1=0.0002, p=0.99) (Table 3S). In contrast, the analysis of the Chinese data that included English PW reading proficiency (Chinese_LME_PW) was not significantly different from the one that did not (Chinese_LME). These analyses show that English PW reading proficiency modulated the effectiveness of stimulation of the dorsal pathway for English word reading but not for Chinese character reading.

Similarly, LMEs for Chinese (and English) were reanalyzed, including the pinyin proficiency score as a covariate. Importantly, the significant effect following dorsal stimulation seen in the Chinese_LME model was no longer significant (β_1=−0.02, p=0.94). However, the ventral stimulation effect remained significant, (β_1=0.82, p=0.008; refer Table 4S). The difference between the models with and without the pinyin proficiency variable reveals that while pinyin proficiency affected tDCS modulation of the dorsal pathway for Chinese word reading, stimulation of the ventral pathway was unaffected by pinyin proficiency. It was also found that the dorsal pathway stimulation effect for English reading did not change following the inclusion of the pinyin reading proficiency score (English_LME_pinyin, Table 4S). These analyses (Table 4S) showed that pinyin proficiency modulated stimulation effects (only) in the dorsal pathway for Chinese reading but not for English reading.

Overall, the above analyses show that after the inclusion of proficiency scores in the English and Chinese LMEMs as a covariate, the dorsal pathway stimulation effects were no longer significant. The findings imply that in both the languages, dorsal stimulation might not enhance reading if the variance in the script-specific sub-lexical proficiency scores (PW and pinyin) are controlled across the participants. The logical question that follows is to explore the nature of the relation of these proficiency scores with the dorsal pathway stimulation effect in each language. Thus, post-hoc analyses were performed as follows.

(3) Post-hoc analyses for proficiency: The post-hoc analyses were conducted using linear regression between the effects of stimulation of word reading RTs (*post – pre RTs*) for dorsal, ventral and sham conditions (dependent variable) and the sub-lexical processing scores (independent variables) for both the scripts (PW and pinyin). With PW scores as the predictor, the regression results revealed a statistically significant tDCS modulation effect (p=0.02) for English word reading (Figure 7A) but not for Chinese (p=0.5; Figure 7B) for dorsal pathway stimulation. Further, the PW reading scores were negatively correlated (−0.75) with the change in reaction times for dorsal pathway stimulation, indicating that the participants with lower PW reading scores had larger stimulation effects. Similarly, with pinyin as a predictor, the regression results revealed statistically significant tDCS modulation (p=0.04) for Chinese character reading (Figure 7D) but not for English (p=0.7; Figure 7C) for dorsal pathway stimulation. As with the PW scores, the correlation between pinyin and dorsal pathway stimulation effects were negative (−0.56), indicating lower pinyin scores resulted in large stimulation effects in the dorsal pathway. The fact that English PW scores does not predict tDCS effect in Chinese reading, and likewise, Chinese pinyin scores fails to predict tDCS effect in English reading, is consistent with the finding that PW scores and pinyin scores are not correlated amongst themselves (0.33).

(4) Gender-related differences in tDCS effect: We also used LME modelling to evaluate the impact of gender on tDCS effects, combining the RTs of both the languages and including language as a covariate. The change in RT (post-pre) served as the dependent variable in the model. The interaction effects of gender with dorsal (β_1=0.15, p=0.02) and ventral stimulation (β_1=0.17, p=0.02) were found to be significantly different from sham stimulation. The estimation of marginal means for the model showed males (dorsal: 45.17 ± 30.44; Ventral: 41.44 ± 30.44) exhibited larger stimulation effects on change in RT compared to females (dorsal: 14.07 ± 30.44; ventral: 19.35 ± 30.44) for both pathways. The raw data distribution of trial averages in English and Chinese languages for 8-male and -female participants are plotted in Figure 8. We also performed the sensitivity analysis (±95% confidence interval) with multiple simulations of the model (Green & MacLeod, 2016). Given the number of observations of 760 [8 participants × 90 trials per participant that included both the languages)] per condition (male and female), we had the power of 80% (44.39, 97.48) at alpha=0.05 to detect the observed difference in gender due to stimulation condition.

4 Discussion

The present study aimed to use tDCS to stimulate the left dorsal and ventral reading pathways in Chinese-English (C-E) bilinguals to evaluate the influence of the orthographic depth of the script on the recruitment of these pathways in reading English and Chinese words. First, we found that tDCS modulated reading in both pathways for Chinese readers but in only the sub-lexical pathway for English readers (Figure 6). We assume that this is due to greater exposure and proficiency in English reading than Chinese reading, which occurred (Figure 5A-D) despite, recruiting early bilinguals. Second, we found that that tDCS effects were also modulated by individual participant's sub-lexical reading levels (Figure 7)). Specifically, in both languages, the sub-lexical dorsal pathway stimulation effects were modulated by sub-lexical reading proficiencies in each language (PW and pinyin). Third, we found a gender difference in tDCS-induced modulation of behavioral responses such that males showed larger tDCS effects than females (Figure 8).

4.1 Proficiency influences the tDCS-induced stimulation effects in bilingual reading

In the present study, tDCS was found to successfully modulate word reading in both of the languages of C-E bilinguals. The improvements (faster word reading times) were observed following sub-lexical (dorsal) pathway stimulation in both English and Chinese and lexical (ventral) pathway stimulation in Chinese only. Based on orthographic depth alone this finding would be surprising as it predicts that English, being an alphabetic language, would recruit the sub-lexical pathway more than Chinese would, and Chinese being a logographic language would primarily recruit the lexical pathway. However, the observed pattern can be understood if we consider the relative proficiencies in the two languages of the C-E bilinguals recruited in the present study. This would predict that for English reading (the language with greater reading proficiency), the lexical pathway would be especially robust, while in Chinese reading (the language with lower reading proficiency), both pathways would be less robust.

Critical for interpreting the observed pattern of results is the previous findings indicating that tDCS produces a greater enhancement of behaviours generated by sub-maximally utilized systems (e.g., in reading, Cancer & Antonietti, 2018; Thomson et al., 2015) as well as other processing tasks (Boggio et al., 2006). On that basis, the higher overall exposure and proficiency scores in English compared to Chinese (Figure 5A-D), could account for the non-significant improvement in English reading efficacy following lexical pathway stimulation. In other words, it is plausible that the bilinguals in this study were utilizing their lexical processing capacity at the maximum level because the present population reflected a ceiling effect with minimal variability in RW naming accuracies (Figure 5E); thereby leaving no room for further improvement following facilitation by tDCS. The observed significant effect in English reading following sub-lexical pathway stimulation could be attributed to lower and variable proficiency in naming PW compared to RW (Figure 5E), suggesting submaximal utilization of the pathway and, therefore, greater room for stimulation-based enhancement. On the other hand, overall lower and more variable exposure and proficiency in Chinese compared to English (Figure 5A-D) allowed for more room for improvement in response to tDCS stimulation of either pathway. This would account for why stimulation of either lexical or sub-lexical pathways resulted in significant facilitation during Chinese reading. It is likely that the large variance amongst the participants within the of CCR and pinyin scores (measures of proficiency in lexical and sub-lexical processing, respectively, Figure 5F,) could account for significant lexical and sub-lexical stimulation effects in Chinese. Therefore, these findings indicate that the relative proficiency in each language of a bilingual may be a factor determining the likelihood of tDCS stimulation effect.

Furthermore, we found that the sub-lexical pathway tDCS-based enhancement of word reading fluency was associated with individual participant's PW accuracy scores. PW (pseudo-words) are novel letter strings that have no meaning and can be read through sub-lexical processing, whereas meaningful words can be named through both lexical and sub-lexical processing, either recruited independently or in combination. Our present findings indicate that participants with lower PW reading scores benefitted more following tDCS facilitation of the dorsal sub-lexical regions while reading the words. Presumably, this was because the degree of enhancement was based on the degree to which the pathway was sub-optimally used for reading. This raises an important question: in participants with lower proficiency in utilizing the lexical processing strategy, could lexical pathway stimulation enhance English word reading? While this question cannot be addressed by the current study as the participants were highly proficient in reading English. It could be evaluated in future studies with less proficient English readers and/ or more challenging English reading tasks.

Similarly, we found that pinyin knowledge, which is a system of reading Chinese written with the Roman alphabet, affected the magnitude of dorsal pathway stimulation effects during Chinese character reading. Beginning Chinese readers use pinyin as a scaffolding tool to learn Chinese characters since it helps them to associate sounds to characters (Lin et al., 2010). With increasing proficiency, there is less need for scaffolding from pinyin. This would result in increased use of the lexical pathway while reading the Chinese characters, as shown in neuroimaging studies (Tan et al., 2005; Xu et al., 2015). The finding in the present study that sub-lexical pathway stimulation effects are influenced by an individuals' pinyin knowledge indicates that individuals with lower ability to map the sound to characters (as measured by pinyin knowledge) benefitted more from tDCS stimulation of sub-lexical pathway compared to their counterparts with high proficiency in pinyin. As for English, it is intriguing to consider if individuals with lower character reading proficiency would benefit more from lexical pathway stimulation. In the present study, no significant correlation was found between CCR scores (a measure of word reading proficiency) and the effect of lexical pathway stimulation in Chinese reading. This could be because CCR might not be a sufficiently sensitive measure of character reading since it tests only the proficiency in naming high-frequency single characters. The hypothesis that baseline word reading, and word processing capacity more generally might determine ventral pathway stimulation effects should be investigated by future task designs using more sensitive measures of lexical processing proficiency.

Overall, the investigation of the influence of orthographic depth in reading pathway recruitment for C-E bilinguals is complex, given the evidence for the differences in exposure and proficiency between the two languages. Accounting for the proficiency differences is important in tDCS studies given the evidence that we have reviewed, indicating that proficiency/learning level may modulate the modulatory impact of tDCS. The improvement in performance for low proficient readers following tDCS opens the door for future investigations of the impact of proficiency in the recruitment of reading pathways in bilinguals.

4.2 Gender modulates tDCS effectiveness

We found that males had larger stimulation effects compared to females both for dorsal and ventral stimulation targets. The finding that males were more affected by tDCS stimulation compared to females can be explained by a recent modeling study by Russell, Goodman, Wang, Groshong, & Lyeth, (2014). They found that higher amounts of current pass through the parietal bone for males compared to females, while such differences were not seen for the frontal bone. They also demonstrated that, on average, males have a greater thickness of cancellous tissues for the parietal bone compared to females. The bone under the scalp is an important factor for determining the amount of current reaching the target region due to its high resistivity. In the present study, the anodes targeting both the dorsal and ventral pathways were placed over/near the parietal bone; thus, it is expected that more current would reach the target region for males compared to females. Our findings of greater tDCS induced change in behavioural response for males indicate that tDCS studies should consider the effect of gender as a factor in any analysis. Here we combined the trials of both the languages to investigate the gender-related difference in the tDCS effect. The findings we obtained provide motivation to examine the gender-related difference in tDCS effects in reading and language processing with a larger sample size.

5 Conclusions

Using tDCS, the present study investigated the modulation of bilingual reading by selectively stimulating the dorsal and ventral pathways of reading. As it is known that the utilization of these pathways within bilinguals depends on the orthographic depth and language proficiency, the influence of these factors on tDCS induced stimulation effects were investigated. We found that the language proficiency of the respective languages in a bilingual contributes to the magnitude of tDCS stimulation effects. In particular, the study found that the stimulation of the ventral, lexical pathway enhanced fluency in Chinese reading only, whereas stimulation of sub-lexical, dorsal pathway enhanced reading in both English and Chinese. We hypothesized that the failure to modulate English reading speed with lexical pathway stimulation was probably due to higher overall proficiency in English compared to Chinese. It was also found that enhancement in reading speed for English and Chinese following sub-lexical, dorsal pathway stimulation was modulated by an individual's PW and pinyin knowledge. Thus, lower sub-lexical reading proficiency was associated with larger stimulation benefits, regardless of the orthographic depth of a language. Additionally, we also found gender-related differences in the magnitude of stimulation effects irrespective of the language, such that males experienced greater stimulation benefits.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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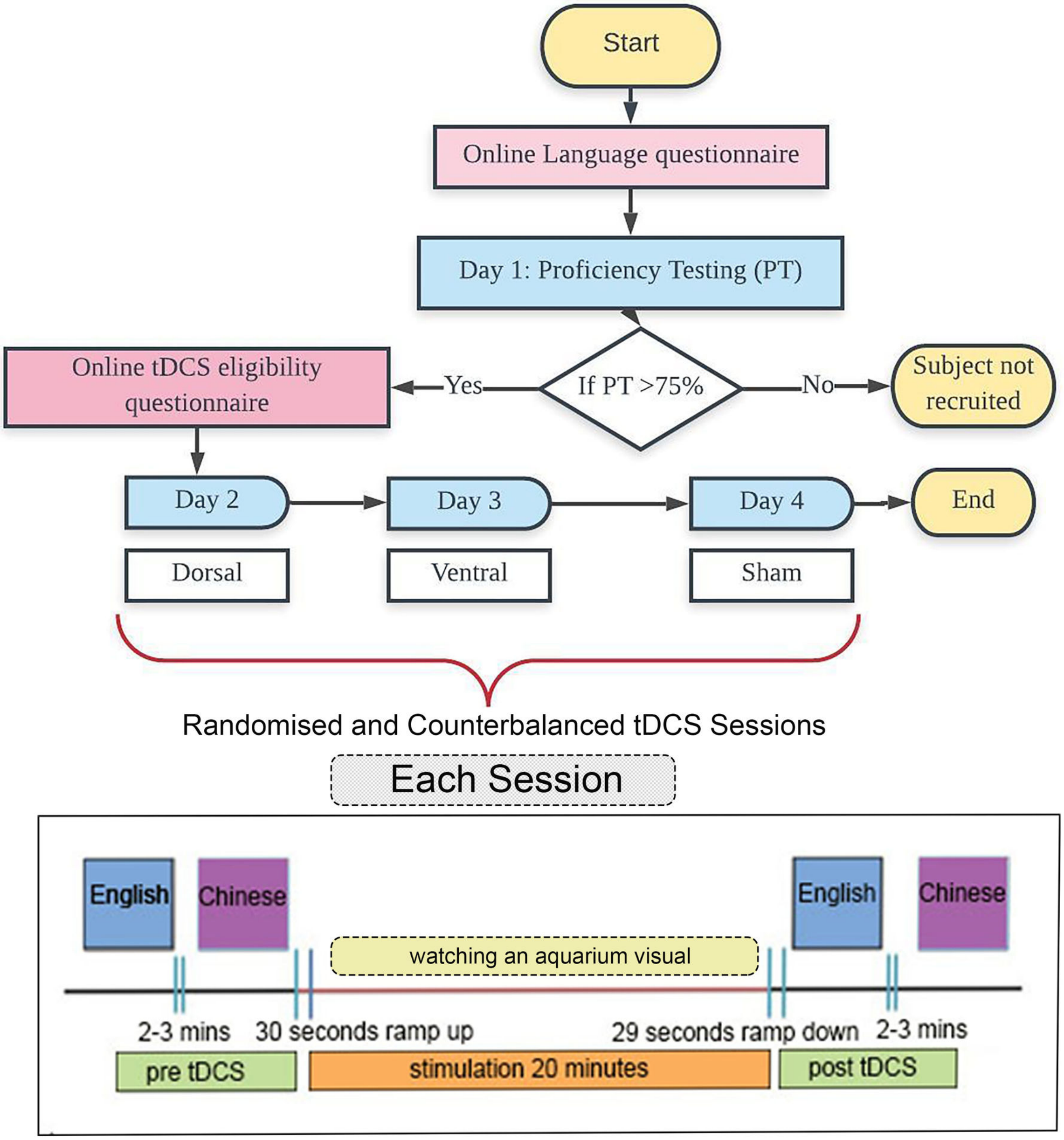


Figure 1.

The flowchart demonstrates the experiment protocol. It shows that the experiment was conducted in four sessions. The participants preliminary selection was based on an online language questionnaire. On Day 1, we measured their word reading fluency in both the languages by using standardised tests. If participants scored >75% in each language, then they were recruited for three identical sessions with different stimulation conditions: dorsal, ventral, and sham (randomized). During each tDCS session, equivalent versions of the rapid naming tasks (RNTs) for each of the two languages were administered before and after stimulation with a gap of 2-3 minutes between languages. The order of language and the RNT versions (6 for each language) were randomized and counterbalanced across sessions for each participant. The tDCS stimulation lasted for 20 minutes in total that included 30 seconds of the ramp-up at the beginning and 29 seconds of the ramp down at the end.

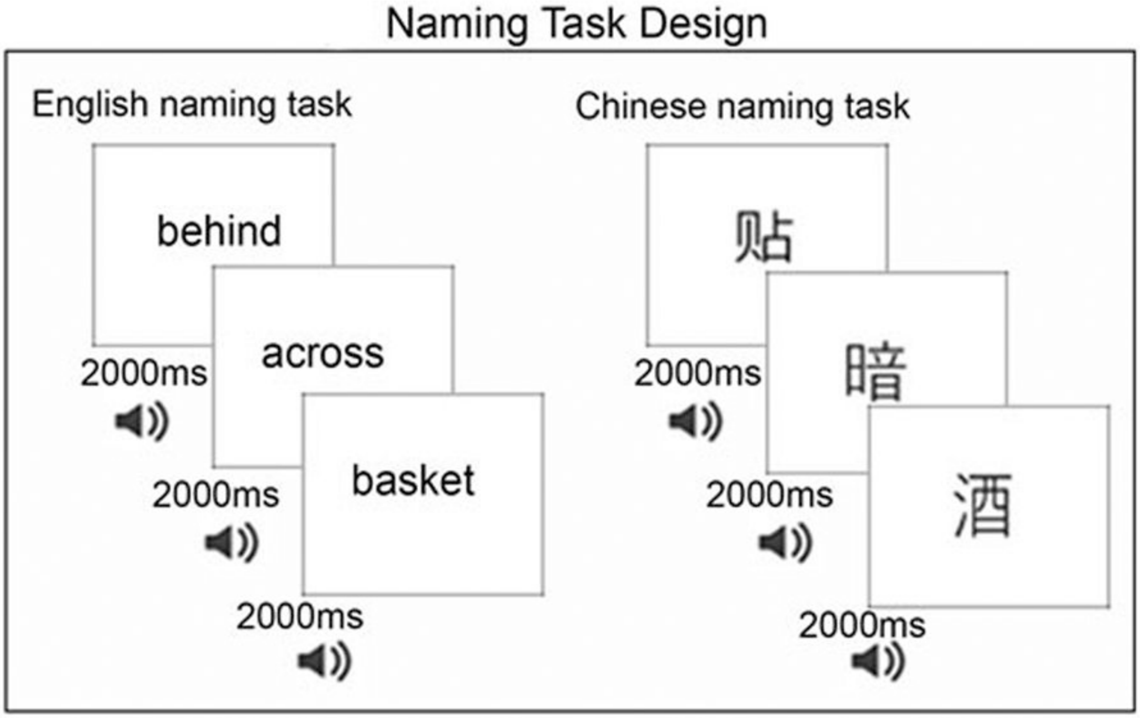


Figure 2:

The presentation of word/character stimuli for English and Chinese rapid naming tasks (RNTs) via E-prime. The responses were recorded for each word/character with the Chronos voice key linked to E prime.

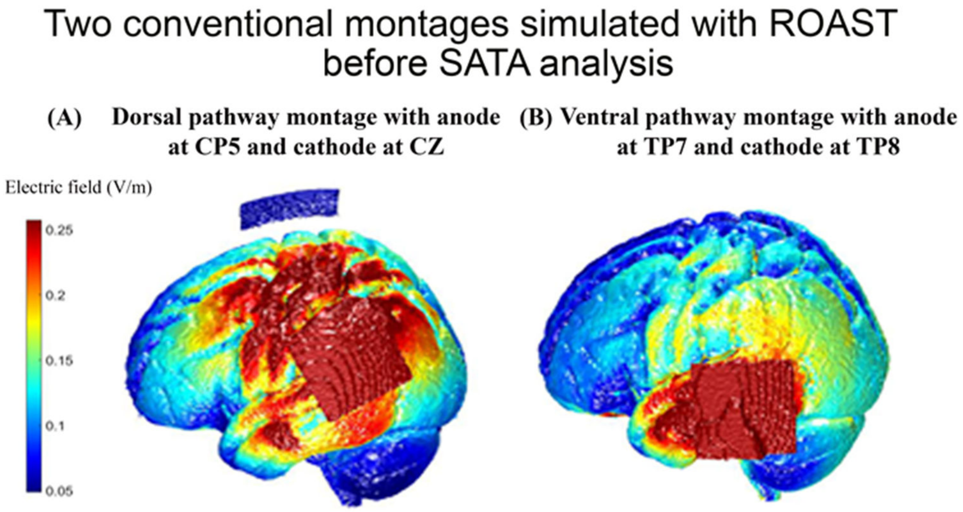


Figure 3:

ROAST simulation output for two montages with a total current intensity of 2 mA (A) anode at CP5, and cathode at CZ for dorsal pathway; and (B) anode at TP7, cathode at TP8 for the ventral pathway.

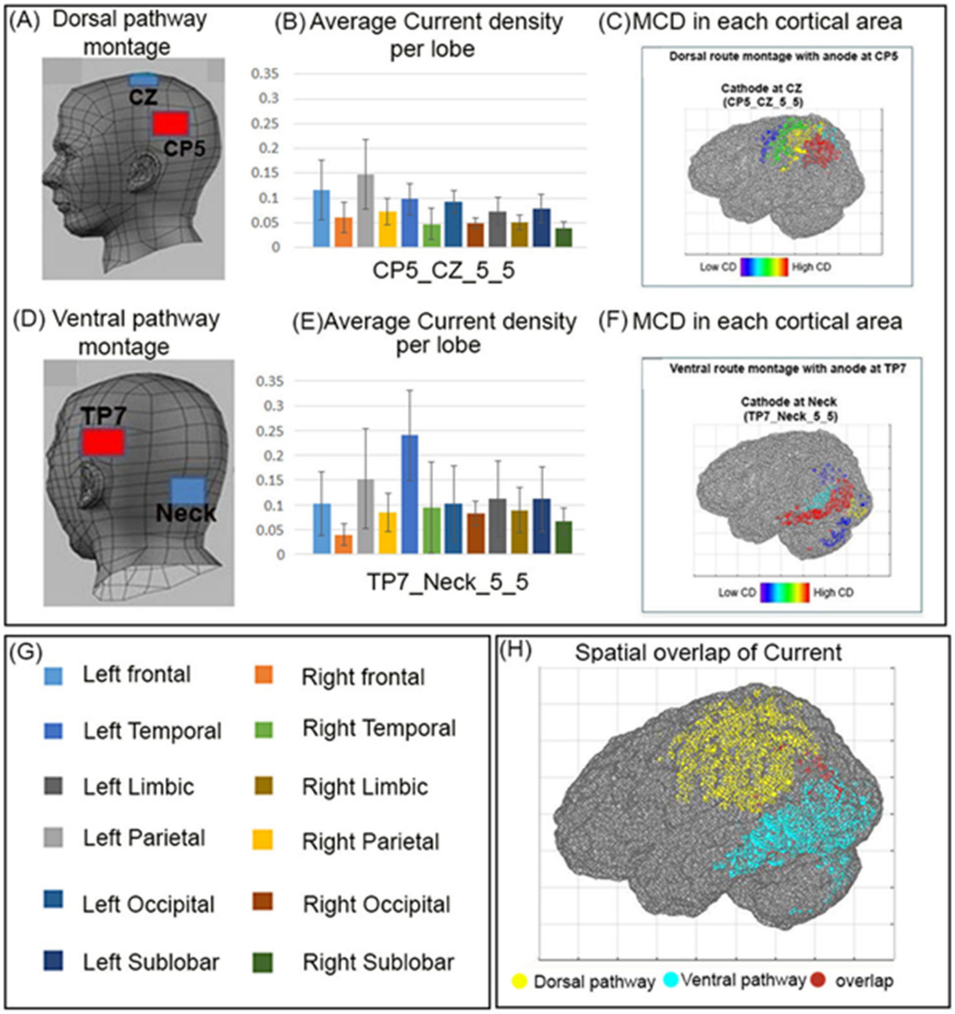
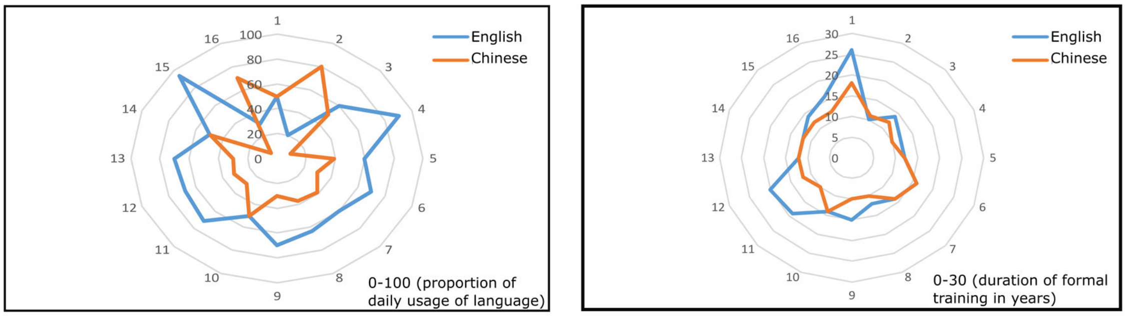
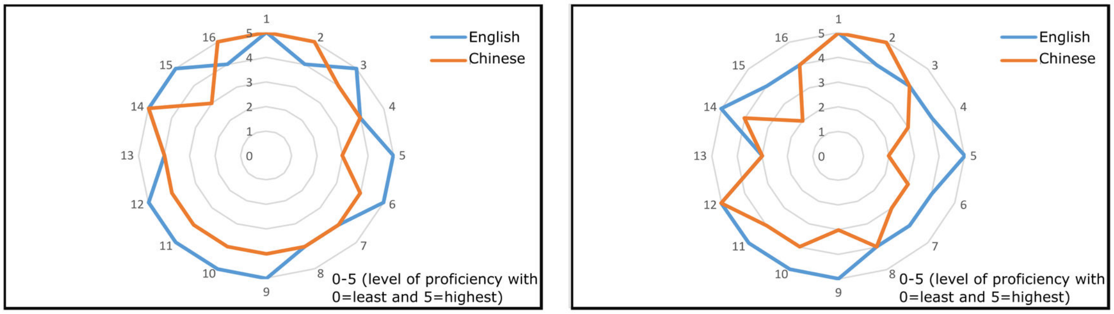


Figure 4:

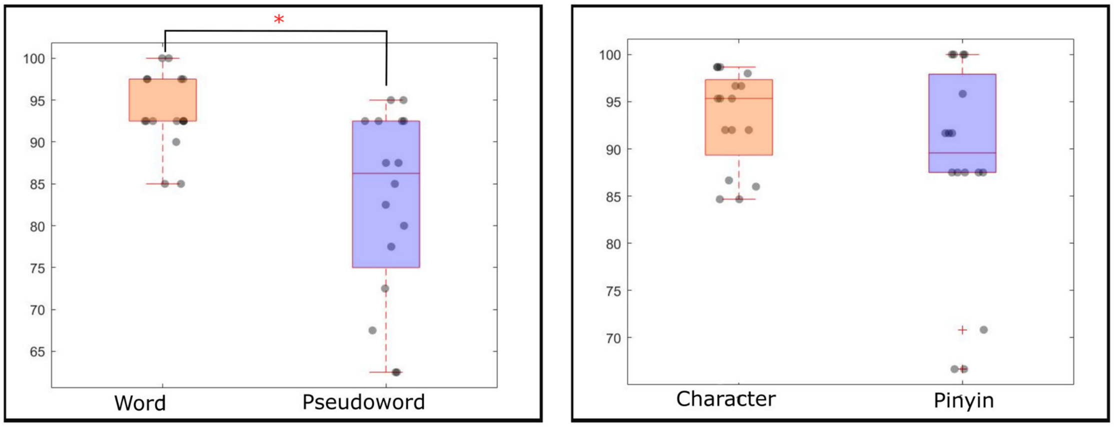
(A) shows the dorsal pathway montage. (B), and (C) show the SATA toolbox outputs of maximum average magnitude of current density (MCD) per lobe and maximum current density per cortical region for dorsal pathway. (D) Shows the ventral pathway montage. (E) and (F) show the SATA output for ventral pathway montage similar to (B) and (C). (G) Shows the figure legends used to describe (B) and (E). (H) Shows the amount overlap in the spatial spread for the dorsal and ventral pathway montages describe in (A) and (D).



(A) Proportion of daily usage for each language (B) Duration of formal training for each language



(C) Profiicency scores in reading for both the langauges(D) Profiicency scores in writing for both the langauges



(E) Word and Pseudoword proficiency scores in English (F) Character and Pinyin proficiency scores in Chinese

Figure 5.

(A) Proportion of daily usage of each language by each participant. The five concentric circles represent the proportion from 0 to 100 for the daily usage of language. (B) Years of formal training for both the languages by each participant. The five concentric circles represent the number of years from 0 to 30. (C) and (D)) Self-rated proficiency scores in English and Chinese across all the participants for reading and writing. The five concentric circles represent scores from 0 (least) to 5 (highest). The blue and orange lines in (A), (B), (C) and (D) show how each participant rated themselves on the respective scales for English and Chinese languages, respectively.(E) A significant difference is seen between real word and pseudo-word reading accuracy scores for English. (F) No significant difference is seen between character and pinyin proficiency scores for Chinese reading.

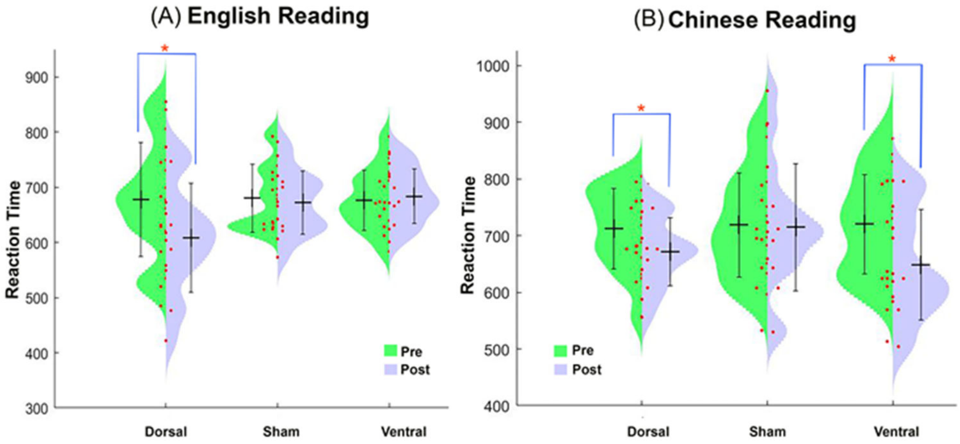


Figure 6:

The raw data distribution for the mean values of all the trials per session (total=six sessions) for each participant (total=16 participants). English and Chinese Language are plotted in A and B, respectively. The six sessions include pre and post-stimulation time points for three stimulation conditions (dorsal, ventral, and sham). Green distribution: pre-tDCS; Purple distribution: post-tDCS; Red dots: trial average for each participant.

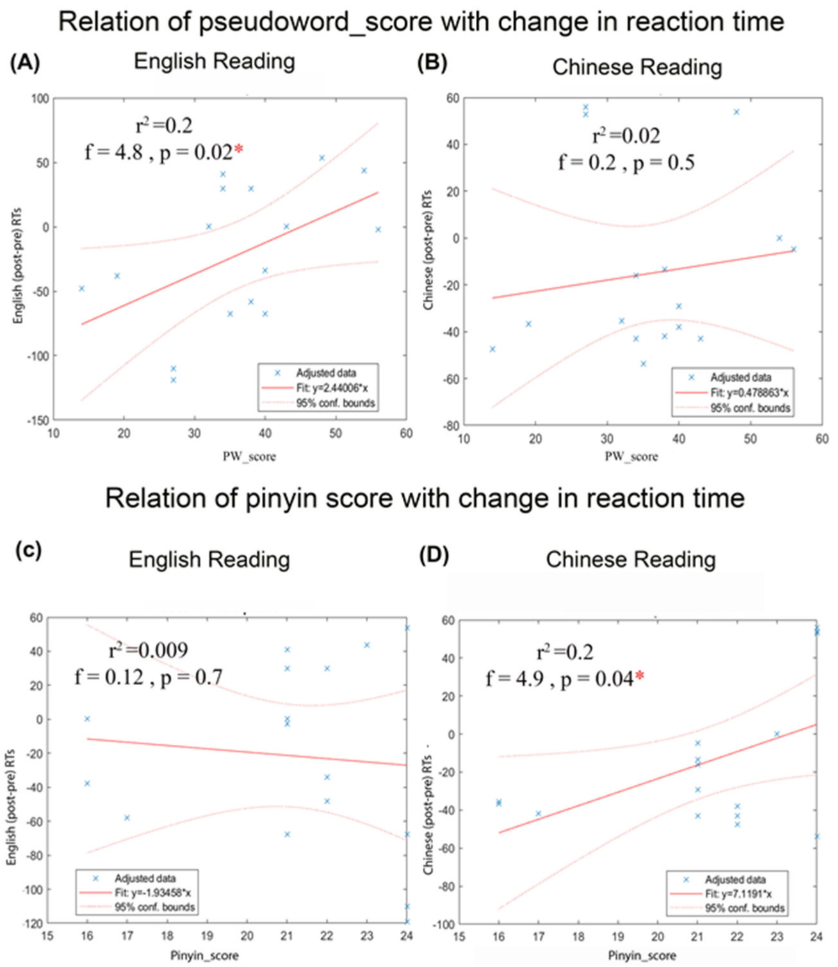


Figure 7:

The effect of pinyin and pseudo-word (PW) proficiency scores on the change in word reading reaction times from pre to post stimulation time points. (A) And (B) depict the regression lines for the pre-post stimulation change in reaction time (y-axis) predicted by pseudo-word (PW) scores (x-axis) for English and Chinese, respectively. Similarly, (C) and (D) depict the regression lines for the pre-post stimulation change in reaction time (y-axis) predicted by pinyin scores (x-axis) for English and Chinese, respectively.

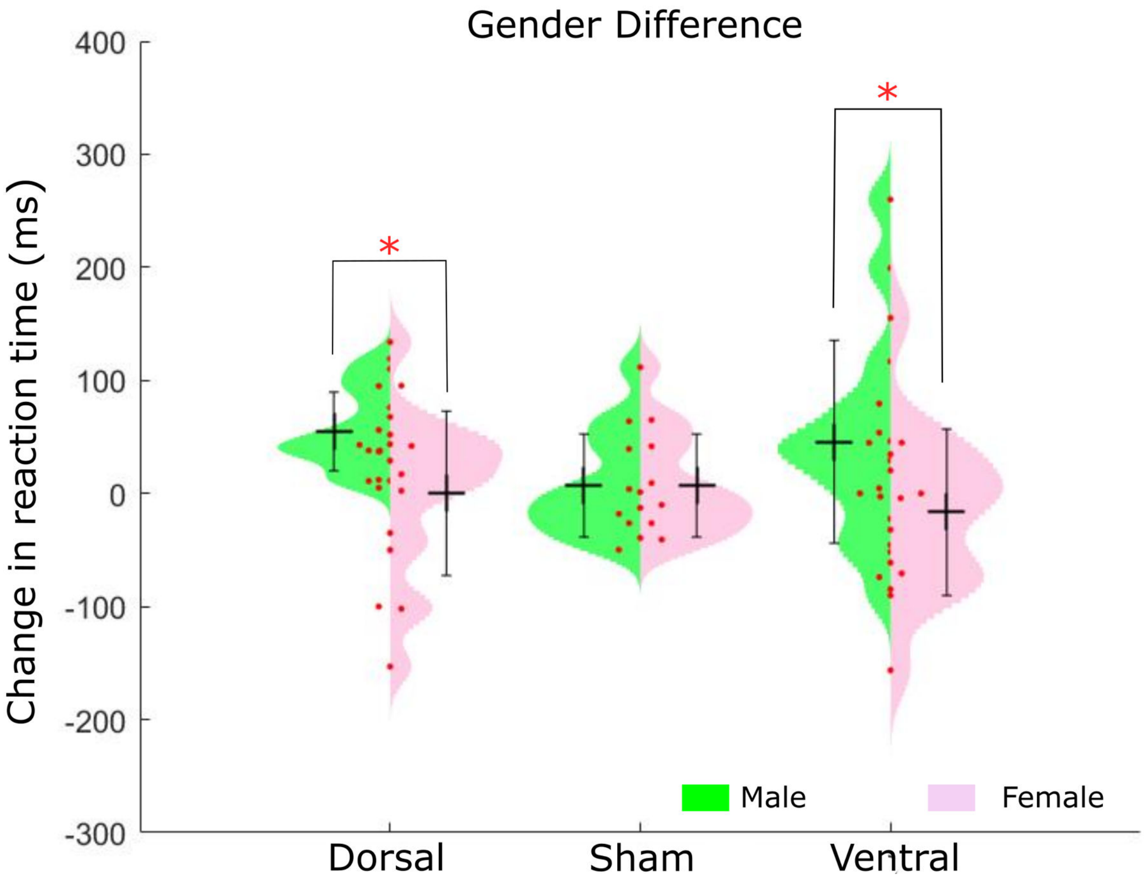


Figure 8.

shows the distribution of raw data for change in reaction time in males and females for dorsal, ventral, and sham stimulation. The distribution plot contains the difference in reaction time for trial averages for both the languages in each participant. The tDCS-induced decrease in RT in males higher compared to females. Green distribution: male; Pink distribution: female; Red dots: trial average for each participant.