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Prefrontal Transcranial Direct Current Stimulation (tDCS) Has a Domain-Specific Impact on Bilingual Language Control

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Researchers debate whether domain-general cognitive control supports bilingual language control through brain regions such as the dorsolateral prefrontal cortex (DLPFC). Transcranial direct current stimulation (tDCS) is a method to alter brain activity, which can lead to causal attribution of task performance to regional brain activity. The current study examined whether the DLPFC enables domain-general control for between-language switching and nonlinguistic switching and whether the control enabled by DLPFC differs between bilinguals and monolinguals. tDCS was applied to the DLPFC of bilingual and monolingual young adults before they performed linguistic and nonlinguistic switching measures. For bilinguals, left DLPFC stimulation selectively worsened nonlinguistic switching, but not within-language switching. Left DLPFC stimulation also resulted in higher overall accuracy on bilingual picture-naming. These findings suggest that language control and cognitive control are distinct processes in relation to the left DLPFC. The left DLPFC may aid bilingual language control, but stimulating it does not benefit nonlinguistic control.

Keywords: control, bilingualism, DLPFC, tDCS

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Second language learners know the difficulty of avoiding slips into their native language. Lifelong experience with two languages trains the brain to select the context-appropriate language—reducing accidental switches—and to intentionally switch between the two languages when appropriate (e.g., Molnar, Ibáñez-Molina, & Carreiras, 2015). This bilingual control may involve similar cognitive control processes to those used to select nonlinguistic contextually appropriate goal-driven behaviors (e.g., taking a new route to avoid traffic; Abutalebi & Green, 2007; Stocco & Prat, 2014). However, recent research has begun to question the similarity of these two types of control, asking, *do they rely on the same brain regions?* and *does experience controlling two languages transfer to nonlinguistic tasks?* (e.g., Paap, Johnson, & Sawi, 2015). Abutalebi and Green (2007) theorized that a network of brain regions contributes to both language control and nonlinguistic cognitive control: the prefrontal cortex (PFC), basal ganglia, inferior parietal lobule, and anterior cingulate cortex. With practice and with increased bilingual proficiency, these brain regions may become more efficient and better able to handle new tasks (Mouthon et al., 2020; Prat & Just, 2008). The current study directly compared the role of the dorsolateral prefrontal cortex (DLPFC) in bilingual and monolingual language control and cognitive control using an experimental approach. The goal of this study was to discover the extent to which between-language switching, within-language switching, and nonlinguistic switching involve similar control processes embodied in the DLPFC in bilinguals and monolinguals.

Focusing on the DLPFC

The target of the current study is the DLPFC. Research has repeatedly implicated the DLPFC in both between-language switching and nonlinguistic switching. For example, the right DLPFC has been associated with between-language switching in functional magnetic resonance imaging (fMRI) research (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001), and applying transcranial magnetic stimulation (TMS) over the left DLPFC has impacted between-language switching in patient populations (Holtzheimer, Fawaz, Wilson, & Avery, 2005; Nardone et al., 2011). Regarding nonlinguistic control, fMRI research has implicated the left DLPFC in learning and executing novel rules (Stocco & Prat, 2014) and increasing conflict during a cognitive control task (Wittfoth, Schardt, Fahle, & Herrmann, 2009), and has implicated the DLPFC in completing two tasks simultaneously (Dux et al., 2009; Kondo, Osaka, & Osaka, 2004).

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Together, these results support the notion that both the left and right DLPFC may be involved in bilingual language control and cognitive control, but differences across studies make it difficult to draw conclusions about the similarities or differences in the DLPFC involvement in language and cognitive control tasks, and whether the similarities or differences depend on bilingual experience. The current study examined whether involvement of the DLPFC depends on either task demands or language experience. Specifically, does the DLPFC impact language and nonlinguistic control similarly, and do bilinguals and monolinguals rely similarly on the DLPFC for both types of control?

Laterality of Language and Cognitive Control in Monolinguals and Bilinguals

Some research suggests that bilinguals recruit more widespread and bilateral brain regions for language than do monolinguals. Whereas monolinguals show neural activity mostly in the left hemisphere for language tasks, research suggests that bilinguals show neural activity in homologous right-hemisphere regions (Jasinska & Petitto, 2013). Activity in right-hemisphere regions is observed particularly when bilinguals are in a "bilingual context" in which both languages may be appropriate for use (Kovelman, Shalinsky, Berens, & Petitto, 2008). In line with previous fMRI research (Hernandez et al., 2001), this suggests that the right DLPFC is particularly important for between-language switching or flexible language use, and less important when only a single language is used.

It is not clear whether recruiting areas of the right hemisphere for language use may influence neural functioning for typically "right hemisphere" activities such as visuospatial functioning. In monolinguals, the left hemisphere is thought to be specialized for language processing, whereas the right hemisphere is specialized for more visuospatial processing (Mellet et al., 2014); however, if bilinguals recruit some right hemisphere regions for language processing, there may also be differences in the activity patterns during visuospatial processing. Consistent with this account, during a shape-color switching task, Garbin and colleagues (2010) observed more fMRI activity in the left hemisphere for bilinguals than monolinguals, but more right hemisphere activity for monolinguals than bilinguals. These results suggest that—unlike monolinguals—bilinguals recruit the right hemisphere for some language tasks and the left hemisphere for some nonlinguistic tasks.

Research to date has not investigated whether these lateralization differences between bilinguals and monolinguals lead bilinguals to use overlapping brain regions for language and cognitive control. If this is the case, it would support the idea that similar control processes underlie both language and cognitive control for bilinguals. Alternatively, finding little overlap in the brain regions involved in bilingual language and cognitive control would raise questions about the relationship between bilingual language control and cognitive control.

Transcranial Direct Current Stimulation (tDCS)

tDCS applies electrical stimulation to a specific area of the brain to either depolarize or hyperpolarize the neurons in that area (Sela & Lavidor, 2014). Depolarization, resulting from anodal stimulation, makes neurons fire more easily, and hyperpolarization, resulting from cathodal stimulation, means that the neurons are less easily excited (Sela & Lavidor, 2014). tDCS is preferable over TMS when the target brain region is large (e.g., DLPFC), and tDCS is generally a cheaper and easier method for research than TMS (Filmer, Dux, & Mattingley, 2014). Prior tDCS studies of both language and cognitive control have focused on the DLPFC. Anodal DLPFC stimulation in healthy populations results in improved response times on cognitive tasks compared with sham stimulation (Dedoncker, Brunoni, Baeken, & Vanderhasselt, 2016). Two studies have specifically examined the effect of DLPFC tDCS on task switching.[1] The first found that anodal stimulation of left DLPFC has affected both linguistic and nonlinguistic switching tasks (Leite, Carvalho, Fregni, Boggio, & Gonçalves, 2013). The second found that both left and right DLPFC anodal tDCS resulted in faster response times for switch and repeat or nonswitch trials compared with sham on a nonlinguistic switching task, suggesting bilateral involvement in switching task performance (Tayeb & Lavidor, 2016). Both previous studies placed the tDCS electrodes symmetrically on DLPFC, confounding left-anodal and right-cathodal stimulation (and vice versa). Because both left and right DLPFC are of theoretical interest, this can complicate the interpretation of the results. The current study instead applied a frequently used tDCS montage (Filmer, Mattingley, & Dux, 2013; Filmer, Dux, & Mattingley, 2014; Metuki, Sela, & Lavidor, 2012) with anodal stimulation of DLPFC and cathodal stimulation to the contralateral supraorbital region, better separating the contributions of the left and right DLPFC.

Current Study

This study has two goals: to test the extent to which bilingual language control and nonlinguistic control rely similarly on the DLPFC (within bilinguals), and to compare linguistic and nonlinguistic control for both bilinguals and monolinguals by focusing on the role of the DLPFC. The first hypothesis is that anodal tDCS over both the left and right DLPFC will result in better performance compared with sham stimulation on between- and within-language switching tasks and a nonlinguistic task for bilinguals. This hypothesis is based on the notion that domain-general cognitive control from the bilateral DLPFC underlies bilingual performance for both language switching and nonlinguistic switching. The second hypothesis is that the effect of tDCS on a within-language switching task and a nonlinguistic switching task will be different for monolinguals and bilinguals. Specifically, monolinguals will show more lateralized effects of tDCS on the two tasks, whereas bilinguals will show less lateralized effects, based on research that suggests that bilinguals recruit more widespread and bilateral regions of the brain for language than monolinguals.

Method

This study took an experimental approach to compare the role of the left and right DLFPC in bilingual and monolingual language control and cognitive control. This study recruited bilingual and monolingual participants to complete between-language switching, within-language switching, and nonlinguistic switching mea-

[1] The two studies discussed here (Leite et al., 2013; Tayeb & Lavidor, 2016) did not report the language backgrounds of their participants.

sures. Participants completed these tasks after undergoing 20 min of 2 mA of tDCS. Three tDCS conditions were implemented: left DLPFC anodal stimulation, right DLPFC anodal stimulation, and sham stimulation. Cathodal electrodes were always placed on a control region (contralateral supraorbital).

Participants

Participants were 78 Spanish-English bilingual students and 64 English monolingual students between the ages of 18 and 35 years old from the University of Houston who were compensated for their time with course credit or Amazon gift cards. Students were screened to determine whether they fit into either of these two groups. Participants were randomly assigned to one of three tDCS conditions: left anodal DLPFC stimulation, right anodal DLPFC stimulation, or sham stimulation. This random assignment led to 26 bilinguals in each group, 21 monolinguals in the left and right anodal DLPFC stimulation group, and 22 monolinguals in the sham group.

Sample Size Justification

Before data collection, power analyses were conducted based on the effect sizes from previous studies. Partial $\eta^2 = 0.25$ for stimulation in the switching study conducted by Tayeb and Lavidor (2016), and partial $\eta^2 = 0.445$ for stimulation in the switching study conducted by Leite and colleagues (2013). According to G-power (Faul, Erdfelder, Lang, & Buchner, 2007), using the more conservative of the two effect sizes (partial $\eta^2 = 0.25$; $f = 0.58$), with an alpha level of 0.05, and power = 0.80, the required sample size for a mixed analysis of variance (ANOVA) with six groups (2 language group × 3 tDCS conditions) and two within-subject measures (task) would be 18 participants per group—assuming the tasks are moderately correlated ($r = .40$). This leads to 54 bilinguals and 54 monolinguals randomly assigned to each of the three conditions: left-anodal stimulation, right-anodal stimulation, and sham. We exceeded this sample size for all groups.

Materials

Screening form. The screening form included demographic information, health information, educational background, language background, and socioeconomic background. These questions were used both for screening and to provide details about the characteristics of the sample recruited. Participants were excluded if they reported a history of vision, hearing, attention, psychological, or language problems, as these could all interfere with performance on the tasks. English monolinguals were included if they reported no languages other than English spoken in their home during childhood, no more than one month spent in a country whose majority language is not English, and no more than 4 years spent taking classes in a foreign language. Spanish-English bilinguals were individuals who learned Spanish as a native language that was spoken in their home during childhood. These bilinguals were excluded if they spent more than one month in a country whose majority language is not English or Spanish or if they took more than 4 years of classes in a language other than English or Spanish. Additional details about the bilingual participants' language background were collected, such as their age of English acquisition, time spent using each language, schooling in each language, and home language environment. Participants who did not qualify as Spanish-English bilinguals or English monolinguals based on this online screening form were disqualified. Participants who qualified based on the screening form were invited to sign up for the tDCS session in the lab.

Woodcock-Muñoz Language Survey–Revised. Language proficiency was measured using the Woodcock-Muñoz Language Survey–Revised (Woodcock, Muñoz-Sandoval, Ruef, & Alvarado, 2005). The picture vocabulary and passage comprehension subtests were given to both bilinguals and monolinguals in both English and Spanish. Monolinguals were assumed to have very little Spanish knowledge, so testing proficiency in Spanish provided a quantitative measure of their limited Spanish proficiency.

Attentional Control Scale. The Attentional Control Scale was developed by Derryberry and Reed (2002) and measured the ability to focus attention, shift attention, and flexibly control thought based on Likert scale responses to 20 items, where 1 = *almost never* and 4 = *always*. Attentional Control scores were calculated as the sum of the 20 items. Participants completed the questionnaire during the lab session using Google Forms on a Dell laptop computer.

Media multitasking index. This questionnaire was designed by Ophir, Nass, and Wagner (2009) to assess how often a participant uses multiple types of media simultaneously (e.g., listening to music while using e-mail). It asked participants to report the number of hours they spend per week on different forms of media (e.g., TV, music, text messaging, and web surfing), and how often they use different pairs of media simultaneously (e.g., watching TV while listening to music). Participants read each pair of media and responded "most of the time," "some of the time," "a little of the time," or "never." The outcome score is the "media multitasking index," a calculated measure of how much time is spent multitasking with media. In the original study, Ophir et al. (2009) found that the media multitasking index is normally distributed with a mean of 4.38 and a standard deviation of 1.52. Participants completed this survey during the lab session using Google Forms on a Dell laptop computer.

Bilingual Switching Questionnaire. The Bilingual Switching Questionnaire was developed by Rodriguez-Fornells and colleagues (2012). The questionnaire consists of 12 items on a Likert scale (never, very infrequently, occasionally, frequently, and always) that assess how often a bilingual switches between his or her languages and whether these switches are intentional or unintentional. In addition, the questionnaire asks participants to report what percent of their day is spent in each language and how their language use has changed at different ages. Specifically, it asks participants to rate on a scale of −3 (Spanish only) to 3 (English only) how often they used English and Spanish at the following ages: before elementary school, during elementary school, during high school, and during adulthood, and in the following contexts at each age: at home, at school/work, in other places. For each age, ratings for at home, at school, and in other places were averaged to create a metric of English/Spanish use across the life span. Bilingual participants completed this questionnaire during the lab session using Google Forms on a Dell laptop computer.

Switching tasks. Separate shape-color, picture-naming, and action-object switching tasks (see Figure 1) were presented to participants using E-Prime 2.0 software (Psychology Software

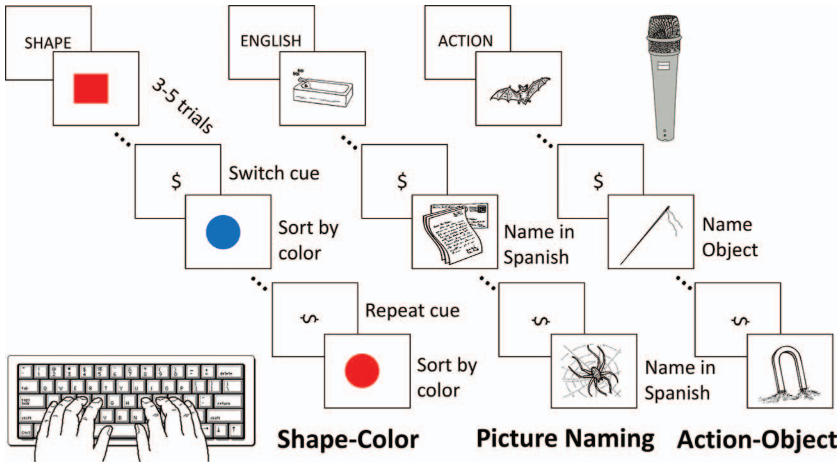

Figure 1. Switching task designs. Responses for the shape-color task were recorded from the keyboard. Responses from the picture-naming and action-object tasks were recorded from the microphone. See the online article for the color version of this figure.

Tools) on a Dell laptop computer running Windows 10. Each task included four runs and participants completed a run of each task before moving on to the next run of each task. The order of the tasks was counterbalanced across participants. Each run of each task lasted about 5 min. Bilingual participants completed all three tasks, and monolingual participants completed the shape-color task and the action-object task. All participants completed a short practice of the shape-color task to ensure they understood which keys on the computer keyboard correspond to which responses. These tasks have been designed to be difficult for young adults, who are at their peak of cognitive performance. Each task provides participants with the starting rule (i.e., shape/color, English/Spanish, or action/object), but then requires that participants maintain and update the rule based on symbolic cues (i.e., horizontal or vertical dollar signs) throughout the rest of the task. Young adult participants find these tasks challenging, which leads to variability in accuracy that is not present in easier tasks, in which most young adults reach ceiling-level accuracy.

Shape-color switching task. The shape-color task was similar to that used in Vaughn and colleagues (2016). Participants viewed bivalent stimuli and indicated either the shape or color of each item. Cues indicating which feature to report were presented after every 3–5 trials for 1,000 ms. On each trial, a fixation cross was presented for 500 ms before the stimulus, which was presented for 1,000 ms. Participants responded by pressing the Z and M keys on the computer's keyboard with their left and right index fingers, respectively. This task was specifically designed to use minimal language. The starting rule is presented in English (i.e., "shape" or "color"), but no other language information is presented during the task. We expect that some participants will use a verbal strategy to complete the task (e.g., thinking "blue/red" or "circle/square"), but the bilingual participants are not prevented from using a similar verbal strategy in Spanish.

Picture-naming task: Bilinguals. The picture-naming task was adapted from Vaughn and colleagues (2016) to match the shape-color task. The same dollar sign cues from the shape-color task were used to indicate switching languages or staying with the same language. These cues were presented every 3–5 trials and lasted 1,000 ms each. Trials involved a 500 ms fixation cross and 1,000 ms stimulus, which were randomly selected from the International Picture Naming Database (Bates et al., 2003). Participants gave a verbal response (naming the picture in English or Spanish) into a microphone. An E-Prime-compatible stimulus-response box equipped with a microphone was used to capture response times for the verbal responses, and the microphone within the Dell Laptop was used to capture the voice recording. Bilingual research assistants assessed the accuracy of each response. They were instructed to make their judgments of accuracy based on the language produced rather than the exact word (i.e., when naming a picture of a duck in English, "duck," "goose," "swan," etc. are acceptable answers; "pato" is not). Two research assistants scored each participant's data, and the interrater reliability of these scores as assessed through Pearson's r was 0.89. When the research assistants disagreed, the final decision was left up to the first author.

Action-object task: Bilinguals and monolinguals. The action-object task was a within-language switching task for monolinguals and bilinguals in which they named the object (e.g., broom) in a picture or named the action associated with that object (e.g., sweep). This task was designed to match the bilingual picture-naming task in format and used pictures from the same database of images (Bates et al., 2003; Szekely et al., 2005) but only included pictures of objects that had obvious actions associated with them (e.g., pencil, write). Any picture whose associated action was identical to the name of the object (e.g., comb, comb) was excluded. This task involved the same nonverbal cues (horizontal and vertical dollar signs) as the picture-naming and shape-color tasks presented every 3–5 trials for 1,000 ms. Like the picture-naming task, the trials included a 500 ms fixation cross and a 1,000 ms stimulus, and participants gave a verbal response into a microphone. Response times were recorded through an E-prime-compatible stimulus-response box equipped with a microphone, and voice recordings were captured through the microphone within the Dell laptop. Bilingual and monolingual research assistants assessed the accuracy of each response. They were instructed to base their judgments on the type of word (action/object) rather than the exact word (i.e., when the picture was a dog chewing on a rope toy and the rule was action, "chew," "tug," "play," etc. are acceptable responses; "dog" is not). Participants were instructed to complete this task in English, so Spanish responses were considered incorrect. Two research assistants scored each participant's data and the interrater reliability as assessed through Pearson's *r* was 0.89. When there was disagreement, the final decision was left up to the first author.

Transcranial direct current stimulation (tDCS). Two milliampere (mA) of anodal tDCS was applied using an electrode size of 35 cm^2 over the left or right DLPFC for 20 min before the start of the tasks. There were three tDCS groups: left DLPFC anodal stimulation (with right supraorbital cathodal stimulation), right DLPFC anodal stimulation (with left supraorbital cathodal stimulation), and sham, which involved the same electrode placement as the left (50%) or right (50%) anodal stimulation groups. During the sham condition, the tDCS stimulator turned on and ramped up to 2 mA of stimulation, just as with the anodal condition, but then immediately ramped back down to 0 mA of stimulation. After 20 min of no stimulation, the tDCS stimulator again ramped up to 2 mA and immediately ramped back down to 0 mA. The ramp up and down each lasted less than 1 min. This allowed the sham participants to experience the tDCS similarly to the anodal participants at the beginning and end of the stimulation, but they did not experience the 20 min of stimulation. Participants were blind to the tDCS condition, and each participant only received only one of these tDCS treatments. Using a between-subjects manipulation further reduced the possibility that participants might infer the tDCS condition because they could not compare across sham and real stimulation conditions.

The tDCS was administered using the Soterix 1 × 1 stimulator. To ensure correct placement of the anodal electrode over the DLPFC, measurements of the tragion to tragion distance, the nasion to inion distance, and the head circumference were taken and entered into Beam F3 software (Beam, Borckardt, Reeves, & George, 2009). This software provides measurements to find the F3 (DLPFC) location based on the International 10–20 system. The measurements from the vertex and midline of the head were then used to mark the DLPFC location on the head of the participant. After determining the correct location for the anodal electrode, two sponges were soaked with a saline solution (9 g salt/1 L). Six milliliters of this solution was applied to each side of each sponge. The electrodes were placed inside the sponges, which were then placed under an adjustable elastic headband on the participant's head. The headband held the electrodes in place and helped to press them against the scalp for good contact with the skin. The tDCS stimulator displayed contact quality, and the headband was tightened and hair was moved until the contact quality displayed was above 50%. Then, the stimulation started and participants were asked to look at a blank wall and daydream for 20 min. Participants were instructed not to use their cell phones or computers or to talk to the researchers unless they were uncomfortable and wanted to stop the stimulation. No participants requested that the researcher stop the stimulation.

Debriefing form. At the end of the session, participants completed a debriefing form to report any side effects of the tDCS that they may have experienced and to report whether they thought they received real stimulation or sham stimulation. This information was used to ensure that the sham condition was effective and to determine whether side effects differed across groups.

Procedure

Participation in this study took place in a single session. For bilinguals, this session lasted 2 hr and 45 min; for monolinguals the session lasted 2 hr and 5 min. Before the session, participants filled out the online screening form to ensure that they qualified as monolingual or bilingual for the purposes of the study. If they qualified, they were invited into the lab where they gave consent. Then, Spanish-English bilingual research assistants administered the Woodcock-Muñoz Language Survey–Revised in both English and Spanish. Next, participants completed the Attentional Control Survey and Media Multitasking Index on the computer. Bilinguals additionally completed the Bilingual Switching Questionnaire. Participants then received the tDCS treatment for 20 min (i.e., "offline" stimulation). Previous research has compared online and offline tDCS with mixed results (e.g., Dedoncker, Brunoni, Baeken, & Vanderhasselt, 2016; Friehs & Frings, 2019). The current study provided offline stimulation to monitor participant symptoms during the stimulation and avoid potential distraction by such symptoms during already-difficult tasks. After the tDCS treatment, participants completed the switching tasks on the computer, which lasted 40 min for monolinguals and 60 min for bilinguals. The order of the tasks was counterbalanced across participants to control for the passage of time between tDCS treatment and task. Upon completion of the tasks, participants were debriefed about their tDCS experience to determine whether they felt any pain or cognitive effects and whether they thought they received real or sham tDCS stimulation. Finally, participants were thanked and compensated for their participation. Throughout the study, participants had access to Spanish-English bilingual research assistants, so they were able to use Spanish if they felt more comfortable doing so. These participants all attended an English-speaking university, so they generally used English with the research assistants. This protocol was approved by the University of Houston Institutional Review Board.

Analyses

Analyses within bilinguals. Comparisons of between-language switching, within-language switching, and nonlinguistic switching were made using a 3 (tDCS condition: left DLPFC, right DLPFC, sham) × 3 (task) Bayesian ANOVA (Wagenmakers et al., 2018) within the bilingual participants, with the outcome measure being accuracy switch costs (difference between accuracy for trials immediately after a switch cue and accuracy for trials immediately after a nonswitch cue). Previous research suggests that either right or left DLPFC stimulation, or both, may lead to reductions in switch costs (Leite et al., 2013; Tayeb & Lavidor, 2016). The goal of the current study was to determine whether tDCS condition interacts with task in determining switch costs. Theoretically, both the alternative and null hypotheses are meaningful. If between-language switching, within-language switching, and nonlinguistic switching rely on different neural substrates, this would make the theory of transfer from bilingualism to cognitive control more difficult to support, but if between-language switching, within-language switching, and nonlinguistic switching rely on the same neural substrates, this would support the transfer theory. Therefore, rather than taking a null hypothesis significance testing approach, the current study applied Bayesian statistics to determine which of two hypotheses better fit the data. The first hypothesis is the task-differences hypothesis—that tDCS affects the tasks differently. The second hypothesis is the task-similarities hypothesis—that tDCS affects the tasks in the same way.

Bayes factors (BF) were computed using JASP (JASP Team, 2018). Default priors were used (Rouder, Morey, Speckman, & Province, 2012), and model comparisons were conducted between the task-differences hypothesis and task-similarities hypothesis (see Table 1). The task-similarities hypothesis used a model that contained only the main effects of tDCS condition and task; the task-differences hypothesis used a model that included the main effects of tDCS condition and task as well as their interaction. The results were interpreted in terms of BF_{10} and BF_{01}. In this analysis, BF_{10} is the ratio of the likelihood of the task-differences model to the likelihood of the task-similarities model. Larger BF_{10} values support the task-differences hypothesis, that is, that tDCS affects between-language switching and nonlinguistic switching differently. BF_{01} is the inverse of BF_{10}; it is the ratio of the likelihood of the task-similarities model to the likelihood of the task-differences model. Larger BF_{01} values support the task-similarities hypothesis, that is, that tDCS affects both between-language switching and nonlinguistic switching similarly. Finally, BF_{10} and BF_{01} may both be very close to 1. When this is the case, the data provide no evidence for either the task-similarities or task-differences hypothesis. The magnitude of the BF indicates the strength of the evidence for or against a hypothesis, with values of 1–3 indicating "weak" or "anecdotal" evidence and values around 20–30 representing "strong" evidence (see Jarosz & Wiley, 2014 for more detail). Researchers tend to agree that BFs greater than three should be taken as "positive" or "substantial" evidence for or against a hypothesis (Jarosz & Wiley, 2014; Jeffreys, 1961; Raftery, 1995).

Analyses comparing bilinguals and monolinguals. The next question is whether within-language switching and nonlinguistic switching rely on the same neural substrates for bilinguals and monolinguals. Because the theoretical question involves competing hypotheses (i.e., *are the neural substrates the same or different across language groups?*), a Bayesian ANOVA was again used to compare these hypotheses.

To determine whether within-language switching and nonlinguistic switching rely on the same or different neural substrates within each language group, a 2 (Language Group) × 3 (tDCS condition) × 2 (task) Bayesian ANOVA (Wagenmakers et al., 2018) was conducted. The outcome of interest was again switch costs. The bilinguals were expected to either show a similar pattern of switch costs as the monolinguals or show better performance on both tasks under one or both anodal tDCS stimulation conditions (as discussed for the analyses within bilinguals). Once again, Bayesian methods were used because it was theoretically meaningful to test whether bilinguals and monolinguals have similar or different responses to the tDCS conditions across tasks (see *Analyses within bilinguals* for description of BFs). The two hypotheses compared were the group similarities hypothesis and the group differences hypothesis (see Table 1). The group similarities hypothesis was that bilinguals and monolinguals would show similar responses to the tDCS on each task. The group differences hypothesis was that bilinguals and monolinguals would differ in their responses to the tDCS on each task. Here, the model for the group-similarities hypothesis included tDCS condition, task, and their interaction; the model for the group-differences hypothesis included tDCS condition, task, and language group (bilingual/monolingual), and all possible interactions among those variables. If the analysis resulted in more support for the group-similarities hypothesis (i.e., larger BF_{01} values; bilinguals and monolinguals responded similarly to both tasks and to all three tDCS conditions), this would provide evidence against the idea of a "bilingual advantage" mediated by the DLPFC and against the theory of transfer from bilingualism to nonlinguistic control tasks. If, on the other hand, the analysis resulted in more support for the group-differences hypothesis (i.e., larger BF_{10} values), this would suggest that bilingualism changes the way that the brain handles either language switching or nonlinguistic task switching.

Results

Language Group

Bilinguals and monolinguals differed in their scores on the Woodcock-Muñoz Language Survey–Revised and in terms of socioeconomic status (see Table 2). Specifically, bilinguals had higher picture vocabulary, $F(1, 136) = 458.09$, $p < .0001$ and

Table 1
Hypotheses and Models for Each Analysis

Hypothesis	Main effects	Interactions
Within bilinguals:	tDCS	tDCS × Task
Task-differences hypothesis	Task	
Within bilinguals:	tDCS	
Task-similarities hypothesis	Task	
Comparing bilinguals and monolinguals:	tDCS	tDCS × Task
Group-differences hypothesis	Task	Task × Language Group
	Language group	Language Group × tDCS
		Task × Language Group × tDCS
Comparing bilinguals and monolinguals:	tDCS	tDCS × Task
Group-similarities hypothesis	Task	Task × Language Group
	Language group	Language Group × tDCS

Note. tDCS = transcranial direct current stimulation.

Table 2
Background Information for Participants in Each tDCS Group

Group	Gender	Age	SES***	English vocab*	Spanish vocab***	English passage comprehension	Spanish passage comprehension***	Attentional control	Media multitasking
Left DLPFC monolinguals ($n = 21$)	13 F	21.60 (4.41)	4.61 (0.86)	42.10 (4.40)	6.81 (5.78)	24.67 (2.80)	5.37 (2.45)	51.24 (7.91)	2.78 (1.05)
Right DLPFC monolinguals ($n = 21$)	16 F	21.62 (4.75)	4.35 (0.90)	43.38 (3.64)	7.81 (3.74)	24.90 (1.87)	6.42 (2.97)	53.33 (7.76)	3.38 (1.49)
Sham monolinguals ($n = 22$)	19 F	20.41 (3.02)	4.47 (1.04)	44.00 (2.65)	7.23 (3.38)	25.32 (3.05)	5.97 (2.46)	53.59 (5.59)	2.77 (1.20)
Left DLPFC bilinguals ($n = 26$)	24 F	22.65 (3.70)	3.81 (1.32)	39.73 (4.03)	39.92 (4.48)	23.35 (3.07)	22.96 (2.55)	50.08 (7.76)	3.05 (1.20)
Right DLPFC bilinguals ($n = 26$)	19 F	21.76 (3.31)	3.90 (1.29)	38.81 (4.08)	39.96 (6.75)	23.15 (2.52)	22.92 (2.64)	54.04 (7.91)	2.94 (1.36)
Sham bilinguals ($n = 26$)	22 F	21.27 (3.11)	4.30 (1.27)	38.81 (4.43)	38.23 (6.17)	22.69 (2.78)	22 (3.53)	53.54 (6.27)	3.19 (1.24)

Note. tDCS = transcranial direct current stimulation; DLPFC = dorsolateral prefrontal cortex; SES = socioeconomic status. Numbers in parentheses indicate standard deviations.
* Indicates difference between bilinguals and monolinguals is significant at $p < .05$. *** Indicates difference between bilinguals and monolinguals is significant at $p < .001$.

passage comprehension, $F(1, 136) = 447.39$, $p < .0001$ in Spanish than did monolinguals, and monolinguals had higher picture vocabulary in English than did bilinguals ($F(1, 136) = 4.18$, $p = .04$; see online supplemental materials for the full distribution of English and Spanish proficiency scores for bilinguals and monolinguals). There were no significant differences in passage comprehension in English between the two groups, $F(1, 136) = 2.73$, $p = .10$. Additionally, monolinguals came from higher socioeconomic status (SES) backgrounds than bilinguals ($F(1, 127) = 17.54$, $p < .0001$; see online supplemental materials for SES correlations with performance on each task). Bilinguals and monolinguals did not differ in their age, $F(1, 135) = 1.26$, $p = .26$, scores on the Attentional Control Scale, $F(1, 135) = 0.30$, $p = .58$, or scores on the Media Multitasking Index, $F(1, 135) = 0.52$, $p = .47$. Degrees of freedom differ across these analyses because of missing data: one participant did not report age of acquisition, multiple people did not report socioeconomic status, and one participant failed to complete the background questionnaires.

tDCS Condition

Because participants were randomized to the three tDCS conditions (left anodal, right anodal, and sham), they were not expected to differ in any background measures. In line with this expectation (see Tables 2 and 3), there were no differences in age, $F(2, 135) = 0.92$, $p = .40$, socioeconomic status, $F(2, 127) = 1.36$, $p = .26$, age of English acquisition, $F(2, 74) = 1.34$, $p = .37$, or percent of daily English use, $F(2, 75) = 0.21$, $p = .81$, or language use across time, $F(2, 75) = 0.49$, $p = .61$. There were also no differences in scores on the Woodcock-Muñoz subtests (English Picture Vocabulary: $F(2, 136) = 0.49$, $p = .62$; English Passage Comprehension: $F(2, 136) = 0.40$, $p = .67$; Spanish Picture Vocabulary: $F(2, 136) = 0.91$, $p = .40$; Spanish Passage Comprehension: $F(2, 136) = 1.00$, $p = .37$) the Attentional Control Scale, $F(2, 135) = 2.20$, $p = .10$, the Media Multitasking Index, $F(2, 135) = 0.24$, $p = .78$, or the Bilingual Switching Questionnaire, $F(2, 75) = 0.79$, $p = .46$.

Overall Task Performance

Across all participants, accuracy was low and variable, which makes interpretation of response times difficult. Therefore, the remaining analyses will focus only on accuracy differences, but similar results for reaction time (RT) can be found in the online supplemental materials. Compared with monolinguals, bilinguals had overall lower accuracy on the shape-color task, $F(1, 130) = 5.07$, $p = .03$, $\eta_p^2 = 0.04$ and lower accuracy than monolinguals on the action-object task, $F(1, 122) = 35.04$, $p < .001$, $\eta_p^2 = 0.22$. There were no differences across the tDCS groups for the shape-color task accuracy, $F(2, 130) = 1.52$, $p = .22$, $\eta_p^2 = 0.02$ or action-object task accuracy, $F(2, 122) = 0.01$, $p = .99$, $\eta_p^2 = 0.00$. For the picture naming task, there was a significant effect of tDCS condition on picture naming accuracy ($F(2, 70) = 3.08$, $p = .05$, $\eta_p^2 = 0.08$; see Figure 2). Post hoc comparisons using Tukey's honest significant difference (HSD) indicated that the left DLPFC stimulation increased picture naming accuracy compared with the right DLPFC stimulation. See Table 4 for the means and standard deviations of accuracy for each task across the tDCS conditions and language groups.

Table 3
Bilingual Language Background for Participants in Each tDCS Group

Group (n = 26 in each)	AoA	Bilingual switching score	Percent daily English use	Language use before elementary school	Language use during elementary	Language use during high school	Language use during adulthood
Left DLPFC bilinguals	4.64 (3.28)	125.77 (36.07)	65.77 (25.6)	−2.77 (0.51)	−0.68 (1.81)	0.63 (1.83)	0.86 (1.82)
Right DLPFC bilinguals	5.23 (3.29)	129.15 (20.11)	69.46 (20.35)	−2.46 (1.1)	−0.97 (1.81)	0.51 (1.87)	0.83 (1.54)
Sham bilinguals	3.69 (3.67)	134.12 (6.52)	67.69 (14.64)	−2.08 (1.44)	−0.55 (1.75)	0.64 (1.69)	0.72 (1.66)

Note. tDCS = transcranial direct current stimulation; DLPFC = dorsolateral prefrontal cortex. Language use at different ages was calculated based on additional questions included in the bilingual switching questionnaire. See "Bilingual Switching Questionnaire" section for a detailed description of this metric. Numbers in parentheses indicate standard deviations.

Results Within Bilinguals

Bayesian model comparisons. To analyze the results within bilinguals, we conducted Bayesian model comparisons on a model that included only the main effects of task and tDCS (task-similarities model) compared with a model that included the main effects and interactions (task-differences model; see Table 1). In bilinguals, there was weak evidence favoring the task-similarities model (P(M) = 0.50, P(M|Data) = 0.26, BF_{01} = 2.90; see Figure 3), which suggests that tDCS had similar effects on performance across tasks.

Main effects of task and tDCS condition. For a complete understanding of these results, we compared various models including task and tDCS condition (see online supplemental materials for detailed model comparisons). The best model was one that included only task (P(M) = 0.20, P(M|Data) = 0.59, BF_{10} = 5.86). Post hoc comparisons indicate that accuracy switch costs in the nonlinguistic task were larger than in either linguistic task (nonlinguistic vs. between-language switching: prior odds = 0.59, posterior odds = 1.49, BF_{10} = 2.54; nonlinguistic vs. within-language switching: prior odds = 0.59, posterior odds = 2.35, BF_{10} = 3.99).

Lack of accuracy costs for linguistic tasks. In line with the main effect of task described above, Figure 3 suggests that accuracy switch costs for the linguistic tasks (picture-naming and action-object) were near zero. In other words, during these tasks, accuracy following a switch cue was similar to accuracy following a nonswitch cue. As shown in Table 4, overall bilingual accuracy for these tasks was around 50%. This means that for about half of the trials, participants successfully produced the correct word (i.e., action seen in the picture, object seen in the picture) in the correct language (i.e., English or Spanish). Given that participants could produce any word or stay silent in response to each trial, accuracy rates around 50% are well above chance-level. Therefore, the lack of an accuracy switch cost cannot be explained by floor effects (nor by ceiling effects, as accuracy was not near 100%). We additionally considered that there may be switch costs in RTs rather than accuracy. Results of models for RT switch costs are presented in the online supplemental materials; the results of the Bayesian model comparisons for RT switch costs were inconclusive (i.e., evidence neither supported nor refuted task and tDCS effects).

tDCS effects on accuracy costs in the shape-color task. Because neither linguistic task elicited the accuracy switch costs we expected, we conducted an additional analysis focused on the tDCS effects on the accuracy switch costs elicited by the nonlinguistic (i.e., shape-color) task. When looking only at the shape-color task, there was a main effect of tDCS condition (Prior probability = 0.50; Posterior probability = 0.84; BF = 5.27; Error % [i.e., numerical accuracy/robustness from repeated sampling {van Doorn et al., 2019}] = 0.02%). Post hoc comparisons indicate that left DLPFC stimulation increases, that is, worsens, accuracy switch costs compared with right DLPFC stimulation (prior odds = 0.59, posterior odds = 9.57, BF_{10} = 16.30). In other words, stimulating the left DLPFC worsens switching accuracy for the nonlinguistic task.

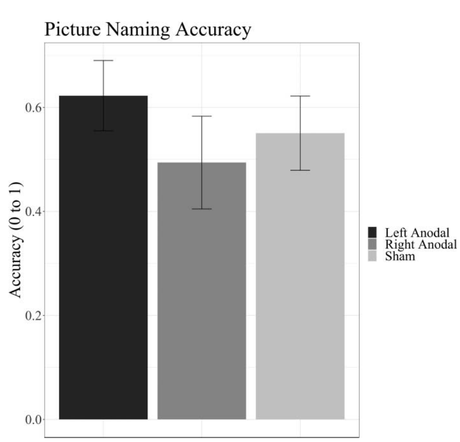

Figure 2. Overall accuracy (proportion correct, 0 = 0% correct, 1 = 100% correct) for bilinguals during the picture-naming task. Left Anodal dorsolateral prefrontal cortex (DLPFC) transcranial direct current stimulation (tDCS) resulted in the highest accuracy for the picture-naming task. Error bars represent 95% confidence interval.

Results Comparing Bilinguals and Monolinguals

Bayesian model comparisons. To analyze the results comparing bilinguals and monolinguals, we conducted Bayesian model comparisons on a model that included only the main effects and two-way interactions of task, tDCS, and language group (group-similarities model) compared with a model that also included the three-way interaction of Task × tDCS × Language group (group-differences model; see Table 1). There was inconclusive evidence for the group similarities hypothesis compared with the group differences hypothesis in terms of accuracy switch costs (P(M) = 0.50, P(M|Data) = 0.43, BF_{01} = 1.31). The model that included a

Table 4
Accuracy on Each Task

Group	Shape-color task		Action-object task		Picture naming	
	Switch trials	Nonswitch trials	Switch trials	Nonswitch trials	Switch trials	Nonswitch trials
Left DLPFC monolinguals (n = 21)	61% (14%)	71% (21%)	56% (14%)	57% (16%)	N/A	N/A
Right DLPFC monolinguals (n = 21)	61% (14%)	71% (16%)	53% (20%)	51% (20%)	N/A	N/A
Sham monolinguals (n = 22)	68% (14%)	74% (20%)	61% (16%)	63% (19%)	N/A	N/A
Left DLPFC bilinguals (n = 26)	62% (14%)	72% (18%)	40% (20%)	42% (18%)	61% (17%)	62% (16%)
Right DLPFC bilinguals (n = 26)	57% (20%)	61% (20%)	42% (21%)	43% (19%)	51% (21%)	50% (24%)
Sham bilinguals (n = 26)	57% (14%)	63% (21%)	33% (19%)	35% (18%)	53% (16%)	56% (16%)

Note. DLPFC = dorsolateral prefrontal cortex. Accuracy is displayed as percent correct. Numbers in parentheses indicate standard deviations.

language group by task by tDCS interaction was neither a better nor worse fit for the data than the model that did not include this interaction.

Language group effects. To develop a complete understanding of these results, we compared all the possible models that included language group effects (see online supplemental materials for detailed model comparisons). The evidence favored similar performance of bilinguals and monolinguals in all tested models (see online supplemental materials data for similar results with RT switch costs). For example, there was evidence against a main effect of language group (P(M) = 0.17, P(M|Data) = 0.18, BF_{01} = 3.63), evidence against a language group by task interaction (P(M) = 0.17, P(M|Data) = 0.010, BF_{01} = 6.74), and strong evidence against a language group by tDCS interaction (P(M) = 0.17, P(M|Data) = 0.03, BF_{01} = 21.54). Overall, these results indicate that bilinguals and monolinguals performed the tasks similarly and were similarly impacted by tDCS.

Task and tDCS condition effects. We additionally compared the models with task, tDCS condition, and their interaction in an attempt to replicate the results seen within bilinguals. As was the case within bilinguals, the best model was one that included only the main effect of task (P(M) = 0.20, P(M|Data) = 0.57, BF_{10} = 46,077.32). Again, it seems that the action-object task did not elicit an accuracy switch cost (see *Results within bilinguals* section for more detail, see Figure 4 for results within monolinguals). Within the shape-color task, there was inconclusive evidence for a tDCS effect across language groups (P(M) = 0.50, P(M|Data) = 0.40, BF_{01} = 1.51). Within bilinguals (as described in the previous section), there was a main effect of tDCS on the shape-color task, but when including the monolinguals in the model, the effect was weakened.

Debriefing Form

The side effects reported in the debriefing form were not significantly different across the tDCS conditions (see Table 5). On average, participants reported very mild to mild difficulty concentrating and fatigue, as well as mild to moderate sensations near the electrodes such as burning, tingling, or itching. Participants could not reliably determine whether they had received real or sham stimulation, and most participants believed the stimulation was real (see Figure 5).

Discussion

This study investigated whether the DLPFC was similarly or differently involved in language switching and nonlinguistic

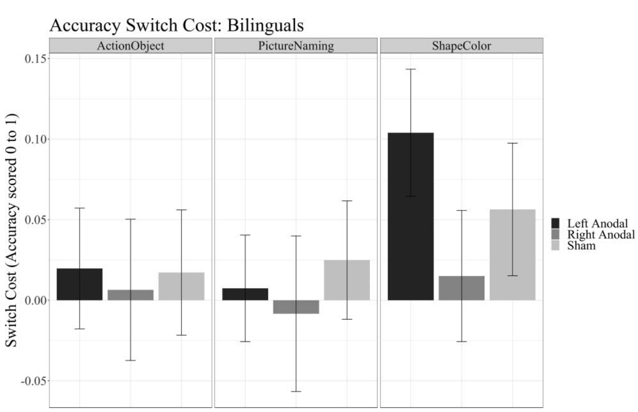

Figure 3. Accuracy switch costs for bilinguals during the picture-naming task, action-object task, and shape-color task. Left Anodal dorsolateral prefrontal cortex (DLPFC) transcranial direct current stimulation (tDCS) worsens accuracy switch costs only for the shape-color task. Accuracy switch costs for the picture-naming task and action-object task are minimal and appear unaffected by tDCS. Error bars represent 95% confidence interval.

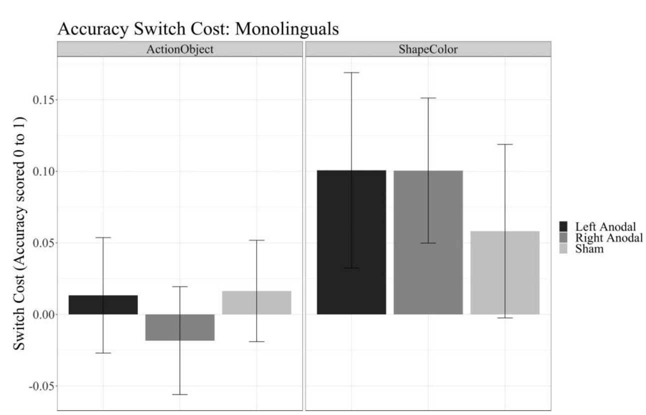

Figure 4. Accuracy switch costs for monolinguals during the action-object task and shape-color task. Accuracy switch costs for the action-object task are minimal and appear unaffected by transcranial direct current stimulation (tDCS). Accuracy switch costs exist for the shape-color task but appear unaffected by tDCS. Error bars represent 95% confidence interval.

Table 5
tDCS Side Effects for Participants in Each tDCS Condition

Condition	Headache	Difficulty concentrating	Change in mood	Change in vision	Fatigue	Sensations (burning, tingling, itching) near the electrodes
Left DLPFC stimulation	0.33 (0.64)	1.64 (1.40)	0.71 (1.22)	0.24 (0.68)	1.38 (1.39)	2.29 (1.01)
Right DLPFC stimulation	0.52 (0.84)	1.63 (1.44)	0.52 (1.13)	0.3 (0.73)	1.33 (1.51)	2.26 (1.10)
Sham stimulation	0.66 (1.09)	1.51 (1.49)	0.7 (1.08)	0.43 (0.85)	1.02 (1.21)	2.3 (0.98)
Kruskal Wallis χ^2 (*df* = 2)	$\chi^2 = 1.50$ $p = .47$	$\chi^2 = .25$ $p = .88$	$\chi^2 = 1.31$ $p = .52$	$\chi^2 = 1.74$ $p = .42$	$\chi^2 = 2.03$ $p = .36$	$\chi^2 = .49$ $p = .78$

Note. tDCS = transcranial direct current stimulation. Side effects were rated on a scale from 0 to 5: 0 = none, 1 = very mild, 2 = mild, 3 = moderate, 4 = severe, 5 = extreme.

switching and whether the involvement of the DLPFC in language switching and nonlinguistic switching was similar or different for bilinguals and monolinguals. Results largely support the conclusion that the DLPFC is differently involved in language control and nonlinguistic control for bilinguals, and that the involvement of the DLPFC in linguistic and nonlinguistic control was similar for bilinguals and monolinguals. Because this study used Bayesian analyses, it is possible to quantify evidence for invariances between bilinguals and monolinguals. This evidence supports the hypothesis that there are no differences between these two groups in the involvement of the bilateral DLPFC in their language control or nonlinguistic control. This study is unique in (a) its comparison of bilinguals and monolinguals each completing a linguistic and nonlinguistic switching task; (b) its use of tDCS to manipulate the DLPFC; and (c) its use of Bayesian statistics to consider both similarities and differences between tasks and between language groups.

Because the interpretation of this study depends on invariances, it is important to show that these invariances did not come from failure to manipulate DLPFC using tDCS. This concern is ruled out by two positive findings from the tDCS manipulation: First, left anodal DLPFC stimulation increased accuracy switch costs for bilinguals during the shape-color task (see Figure 3). Second, left anodal DLPFC stimulation resulted in higher overall accuracy for bilinguals during the picture-naming task (see Figure 2). Unexpectedly, bilinguals and monolinguals showed negligible switch costs on both the picture naming and action-object tasks, which make interpretation of these tasks difficult. This may explain the inconclusive results regarding the task-similarities and task-differences hypotheses.

The finding that anodal left DLPFC stimulation affected overall accuracy during the picture-naming task provides some information about the role of the DLPFC in bilingual language control. The left DLPFC may not be involved specifically in language *switching* for bilinguals, but may be involved in the overall use of

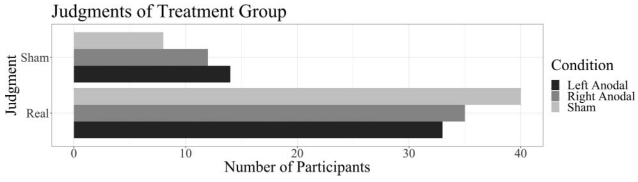

Figure 5. Participant judgments of their treatment group. Most participants believed they received the real stimulation.

two languages (i.e., language mixing). This finding fits with previous work suggesting that the left DLPFC is involved in language selection, but only when bilinguals have lower second language proficiency (Mouthon et al., 2020). Therefore, the left DLPFC may be involved in bilingual language production when it is more effortful (i.e., when proficiency is low or when the task requires frequent language switches). This finding does not fit with the previous research discussed in the introduction that suggests that the *right* DLPFC may be important for bilingual language use (Hernandez et al., 2001; Kovelman et al., 2008).

Additionally, the finding that the left DLPFC stimulation increased accuracy switch costs for bilinguals during the shape-color task runs counter to previous findings that tDCS of the DLPFC improves switching (Dedoncker et al., 2016). More importantly, previous research examining the effects of tDCS of the DLPFC on switching applied the electrodes to the bilateral DLPFC simultaneously, confounding left-anodal and right-cathodal stimulation (and vice versa). The increased accuracy switch costs observed in the current study may be interpreted in light of the lateralization of language or cognitive control in the bilingual brain. Some research suggests that bilinguals may present with greater activity in the left hemisphere for nonlinguistic control tasks than monolinguals (Garbin et al., 2010). The present study suggests that the left DLPFC may be involved in nonlinguistic switching for bilinguals, but that involvement of the left DLPFC may be detrimental, rather than beneficial, to performance, as stimulation of the left DLPFC increased nonlinguistic accuracy switch costs for bilinguals. This suggests that when performing nonlinguistic tasks well, bilinguals may rely less on the left DLPFC.

Overall, the results of this study do not support the hypotheses that were developed based on previous research. Being a bilingual does not seem to alter the functioning of the DLPFC for linguistic and nonlinguistic control tasks. Bilingual language control and nonlinguistic control were both affected by stimulation of the left DLPFC, which could suggest that language and cognitive control rely on overlapping brain regions, but the difference in the direction of the effects (i.e., left DLPFC stimulation improve language control but worsens cognitive control) raises additional questions. A possible account of these results is that bilingual language control is left-lateralized and bilingual nonlinguistic control is right lateralized, but this conclusion is not fully supported by the results of the current study, as nonlinguistic control following right DLPFC stimulation did not differ from sham stimulation. This study makes an important contribution to the field through the use of novel methodology (i.e., tDCS) and statistical methods (i.e., Bayesian analyses), but because the results do not align with the hypotheses, it also raises additional questions for future research.

Limitations

The current study is limited by the use of difficult switching tasks that prevent ceiling effects, but complicate interpretation of response time. We failed to find a switch cost in terms of accuracy for either the picture-naming task or the action-object task, perhaps because accuracy on these tasks was low and variable. The picture-naming and action-object tasks each required verbal responses; therefore, participants could say any word(s) they wanted or stay silent. The shape-color task was more restrictive in the number of possible responses (i.e., the number of keys on the keyboard), and participants were explicitly instructed to place their fingers over the response keys. This means that guessing would produce many more correct responses for the shape-color task (where chance = 50%) than the picture-naming or action-object tasks (where chance approaches 0%), which likely influenced the lower accuracy on these tasks. The action-object task in particular had poor accuracy, with participants frequently naming the object and action together instead of switching, and bilinguals often responding in Spanish rather than English. These results point toward a need for further development of monolingual linguistic switching tasks.

Though all participants were undergraduate students attending the same university, equating their own levels of education, parental education differed across groups. These SES differences are typical of the population of students at this university (Hernandez, Greene, Vaughn, Francis, & Grigorenko, 2015), allowing generalizability to the population. Finally, the current study focused on the DLPFC. Future studies should extend this work to other regions of the brain implicated in both linguistic and nonlinguistic control.

Conclusions and Future Directions

The bilingual brain needs to adapt to use and control two languages (Bialystok, 2017). This may lead some regions of the brain to be repurposed for new language functions (Hernandez et al., 2019; Hernandez, Claussenius-Kalman, Ronderos, & Vaughn, 2018). Using novel methods (i.e., tDCS and Bayesian analyses), the current study suggests that the left DLPFC may be one such region. This study introduced an experimental approach using tDCS to understand the causal effects of the DLPFC on switching and tested competing hypotheses using a Bayesian, rather than null hypothesis testing, statistical approach. These methods provided novel evidence against the bilingual advantage and the transfer of bilingual skills to nonlinguistic skills. These results clarify the connection between language experience and cognitive control. Future research should continue to explore other candidate regions that may underlie this connection. In particular, Stocco and Prat's (2014) Conditional-Routing Model relates flexible language use to flexible rule learning through the basal ganglia. Therefore, although the left DLPFC in bilinguals appears to be most helpful for bilingual tasks, the basal ganglia may support both linguistic and nonlinguistic flexibility. Thus, future studies focused on discovering a potential neural overlap between language control and nonlinguistic control should focus on the basal ganglia; however, these studies will likely need to use different methods because tDCS is ill-suited to stimulating the basal ganglia. These studies will be important to better define how bilingual language experiences relate to nonlinguistic tasks.

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