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Investigating the feasibility of using transcranial direct current stimulation to enhance fluency in people who stutter

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ABSTRACT

Developmental stuttering is a disorder of speech fluency affecting 1% of the adult population. Long-term reductions in stuttering are difficult for adults to achieve with behavioural therapies. We investigated whether a single session of transcranial direct current stimulation (TDCS) could improve fluency in people who stutter (PWS). In separate sessions, either anodal TDCS (1 mA for 20 min) or sham stimulation was applied over the left inferior frontal cortex while PWS read sentences aloud. Fluency was induced during the stimulation period by using choral speech, that is, participants read in unison with another speaker. Stuttering frequency during sentence reading, paragraph reading and conversation was measured at baseline and at two outcome time points: immediately after the stimulation period and 1 h later. Stuttering was reduced significantly at both outcome time points for the sentence-reading task, presumably due to practice, but not during the paragraph reading or conversation tasks. None of the outcome measures were significantly modulated by anodal TDCS. Although the results of this single-session study showed no significant TDCS-induced improvements in fluency, there were some indications that further research is warranted. We discuss factors that we believe may have obscured the expected positive effects of TDCS on fluency, such as heterogeneity in stuttering severity for the sample and variations across sessions. Consideration of such factors may inform future studies aimed at determining the potential of TDCS in the treatment of developmental stuttering.

1. Introduction

Developmental stuttering is a speech disorder affecting 1% of the adult population. The fluency of speech is interrupted by moments of stuttering, which include repetitions and prolongations of speech sounds, and 'blocks' during which speech sounds cannot be produced. Speech therapy for adults who stutter can reduce stuttering symptoms by explicit practice of new speech patterns, such as prolonging phonemes or producing gentle onsets to syllables (Boberg & Kully, 1994; O'Brian et al., 2003; Webster, 1982). However, the benefits do not persist without continued training and practice (Kell et al., 2009; Ward, 2006) making long-term fluency increases difficult to achieve.

People who stutter (PWS) show subtle abnormalities in the structure and function of the brain regions supporting speech. In particular, the inferior frontal cortex (IFC) is consistently highlighted as an affected region. The IFC plays a key role in speech production, comprising regions involved in motor planning as well as integration of sensory signals (Bohland, Bullock, & Guenther, 2010; Guenther, 2006; Hickok & Poeppel, 2007). The first meta-analysis of functional imaging research in developmental stuttering described over-activation of the right IFC as one of three "neural signatures" of stuttering (Brown, Ingham, Ingham, Laird, & Fox, 2005). Two more recent meta-analyses replicated the finding that an over-active right IFC is one marker of the trait of stuttering (Belyk, Kraft, & Brown, 2015; Budde, Barron, & Fox, 2014). Under-activity in the left IFC has been revealed also in several functional imaging studies with PWS (Fox et al., 1996; French et al., 2011; Neumann et al., 2005; Toyomura, Fujii, & Kuriki, 2011; Watkins, Smith, Davis, & Howell, 2008; Wu et al., 1995). Over-activity in the right IFC may compensate for a left hemisphere deficit (Braun et al., 1997; Preibisch et al., 2003). Watkins and colleagues showed that a portion of left IFC – the ventral premotor cortex – was under-active during speaking, and that the white matter underlying this region was disrupted (Watkins et al., 2008). They suggested that this structural deficit affects the integration of sensory and motor information for speech, and the execution of speech motor commands. This hypothesis is in accordance with the results of a meta-analysis of diffusion tensor imaging studies (Neef, Anwander, & Friederici, 2015): white matter integrity is consistently reduced in PWS within the left superior longitudinal fasciculus, including part of the arcuate fasciculus. The affected tracts connect inferior frontal regions (including

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ventral pre-motor and motor cortex, and IFC pars opercularis) with parietal (inferior parietal lobule, supramarginal and angular gyri), and temporal cortex (superior and middle temporal gyri).

It has been proposed that non-invasive brain stimulation to left IFC could increase speech fluency in PWS by supporting more stable activation of sensori-motor plans within oro-facial primary motor cortex (Neef, Hoang, Neef, Paulus, & Sommer, 2015). The excitability of oro-facial motor cortex is altered in PWS relative to fluent speakers (Neef, Hoang, et al., 2015; Neef, Paulus, Neef, von Gudenberg, & Sommer, 2011). Specifically, the excitability of the tongue motor cortex is enhanced in the left hemisphere during transitions between speech gestures in fluent speakers, but this left-lateralised enhancement of excitability is absent in PWS (Neef, Hoang, et al., 2015). The lack of left-lateralisation of motor activation in PWS is consistent with less efficient communication between the left IFC and motor cortex affecting timely planning of motor sequences. This suggestion is further supported by findings using magnetoencephalography to measure the timing of brain activity during single word reading, which showed that PWS activate left motor cortex prior to left IFC, a reversal of the timing seen in fluent speakers (Salmelin, Schnitzler, Schmitz, & Freund, 2000).

One form of non-invasive brain stimulation that shows promise in the treatment of speech disorders is transcranial direct current stimulation (TDCS). TDCS modulates neuronal excitability by slightly shifting the resting membrane potential of cells (hyper- or de-polarising, depending on current direction). Variation in the placement of the positive (anode) and negative (cathode) electrodes during TDCS affects neuronal excitability and behaviour in different ways, and interacts with other factors such as the duration and intensity of stimulation. For example, placing the anode over the primary motor cortex, and the cathode over the contralateral supra-orbital ridge of the forehead increases neuronal excitability in the primary motor cortex (Nitsche & Paulus, 2000). Such stimulation improves motor task performance and learning (Nitsche et al., 2003; Reis et al., 2009). Furthermore, anodal stimulation outside of the motor cortex also has positive effects on targeted behaviours (Holland et al., 2011; Iyer et al., 2005). Critically, the effects of TDCS on behaviour depend upon stimulation being administered in combination with some task that itself engages the targeted brain region in that behaviour. This combination of stimulation and task is key to the promotion of long-lasting behavioural effects (Reis & Fritsch, 2011). TDCS current flow is relatively non-focal, meaning that current is likely to disperse across the targeted region as well as other regions. However, when the target region is activated by a task during TDCS, ongoing plasticity changes in this region can be reinforced by the neuromodulatory effect of TDCS (Bikson, Name, & Rahman, 2013; Reis et al., 2015; Stagg et al., 2011).

Studies in healthy participants have shown that speech and language skills can be improved using anodal TDCS to the left IFC. For example, combining anodal left IFC stimulation with a single session of a "tongue-twister" task resulted in increased articulatory skills following the task (Fiori, Cipollari, Caltagirone, & Marangolo, 2014), and anodal left IFC stimulation reduced reaction times during a naming task (Holland et al., 2011). Performance on artificial grammar learning (de Vries et al., 2010) and verbal fluency (Iyer et al., 2005) also improved in healthy people, following anodal left IFC stimulation. Patients with non-fluent aphasia show improved naming ability after TDCS to the left IFC (Baker, Rorden, & Fridriksson, 2010; Fiori et al., 2010; Monti et al., 2008) and anodal TDCS to the left IFC combined with articulatory training improved speech in patients with acquired apraxia of speech (Marangolo et al., 2011, 2013).

The effect of TDCS on developmental disorders of speech and language, including developmental stuttering, has not been investigated to date. A potential concern related to stimulating the malfunctioning speech production system in PWS is that it may increase stuttering. To mitigate this possibility, we decided to apply TDCS concurrently with a temporary fluency enhancer that would promote plasticity in association with fluent speech production. We chose to use choral speech, which involves speaking in unison with another person and induces complete fluency in adults who stutter (Cherry & Sayers, 1956; Kalinowski & Saltuklaroglu, 2003; Kiefte & Armson, 2008; Saltuklaroglu, Kalinowski, Robbins, Crawcour, & Bowers, 2009). The effects of choral speech, like other fluency 'inducers', are temporary, however, and stuttering typically returns as soon as the second speaker's voice is withdrawn (Kalinowski & Saltuklaroglu, 2003).

In the current study, we investigated the feasibility of a single-session of anodal TDCS over the left IFC to prolong the temporary fluency induced by choral speech in PWS. The temporary fluency enhancements caused by choral speech also temporarily normalise activity in the left IFC in PWS (Fox et al., 1996; Wu et al., 1995), similarly to the 'normalisation' of the speech network shown following a course of fluency therapy (De Nil, Kroll, Lafaille, & Houle, 2003; Neumann et al., 2005). However, compared to fluency therapy, choral speech gives a relatively effortless, immediate fluency, and does not compromise speech naturalness. We hypothesised that choral speech would induce a 'fluent mode' of speech and normalise functioning of the left IFC, and that application of TDCS over the left IFC during this state would promote plasticity associated with speech network activity during fluent speech, e.g. timely communication between left IFC and motor cortex of the articulators. Together these effects would prolong the duration of the 'fluent mode' resulting in measureable reductions in stuttering for the TDCS session relative to the sham stimulation session. We predicted that the fluency enhancing effect of choral speech would not persist in the sham session, and that stuttering rates would return to baseline levels once the fluency enhancer was withdrawn.

2. Methods

2.1. Participants

Sixteen right-handed native English speakers (2 female) took part in the study. All participants were diagnosed with developmental stuttering by a registered Speech and Language Therapist. The mean age of the participants was 30 years (range: 19–58 years). Participants had no history of any communication disorder or neurological impairment, other than developmental stuttering. All participants reported normal hearing and normal (or corrected-to-normal) vision. The Stuttering Severity Instrument, version 3 (SSI-3: Riley, 1994) was used as a standardized measure of stuttering symptoms. The average score across participants on the SSI-3 was 19.4, which is classified as mild (range: 7–28; borderline to moderate stuttering severity). The NRES Committee South Central Oxford C: (11/SC/0482) approved the study. Participants gave their written informed consent, as per the procedure approved by the ethics committee.

2.2. Procedure

Each participant completed two experimental sessions that were separated by at least one and no more than two weeks. In each session, they read sentences out loud while listening to another person reading the same sentences. This choral speech practice lasted 20 min and was completed concurrently with anodal TDCS in one session, and sham stimulation in the other. The order of the TDCS and sham sessions was counterbalanced across