

The effect of transcranial direct current stimulation on task processing and prioritisation during dual-task gait.

James G. Wrightson<sup>1</sup> Rosie Twomey<sup>1</sup> Emma Z. Ross<sup>1,2</sup> and Nicholas J. Smeeton<sup>1</sup>

<sup>1</sup> The Centre for Sport and Exercise Science and Medicine (SESAME), University of Brighton, Eastbourne, East Sussex, United Kingdom

<sup>2</sup>English Institute of Sport, Bisham Abbey National Sports Centre, United Kingdom

The effect of transcranial direct current stimulation on task processing and prioritisation during dual-task gait.

## Abstract

The relationship between cognition and gait is often explored using a dual-task gait paradigm, which represents the ability to divide cognitive resources during walking. Recent evidence has suggested that the prefrontal cortex is involved in the allocation of cognitive resources during dual-task gait, though its precise role is unclear. Here, we used anodal and cathodal transcranial direct current stimulation (tDCS) to probe the role of the prefrontal cortex in the control of stride time variability (STV), trunk RoM and cognitive task performance during dual-task gait. As task difficulty has been shown to mediate the dual-task cost, we also manipulated walking speed to see if the effects of tDCS on dual-task gait were influenced by walking difficulty. Ten adults performed a serial subtraction task when walking at either preferred walking speed or at 25% of preferred walking speed, before and after receiving tDCS of the left prefrontal cortex. Anodal tDCS reduced STV and the dual-task cost on STV, and improved cognitive task performance. Cathodal tDCS increased STV and appeared to increase the dual-task cost on STV, but did not affect cognitive task performance. There was no effect of tDCS on trunk RoM and the effects of tDCS were not mediated by walking speed. The effect of dual-task gait on stride time variability and cognitive task performance was altered by the application of tDCS, and these effects were polarity dependent. These results highlight the role of the prefrontal cortex in biasing task performance during dual-task gait and indicate that tDCS may be a useful tool for examining the role of the cortex in the control of dual-task gait.

## Keywords

Non-invasive; Cognition; Prefrontal cortex; Stride; Variability;

## 1 Introduction

2 A growing body of evidence supports a link between gait and cognition. Rather than being an automated task  
3 requiring little top down control, the control of gait involves high-level cognitive processes (Woollacott and  
4 Shumway-Cook 2002; Yogev-Seligmann et al 2008). The relationship between cognition and gait performance  
5 is typically explored using a dual-task (DT) gait paradigm, which probes an individual's capacity to divide and  
6 allocate cognitive resources during walking (Yogev-Seligmann et al 2008; Al-Yahya et al 2011). During DT  
7 gait, participants simultaneously perform a cognitively demanding task whilst walking. Changes in walking  
8 performance, cognitive task performance, or both, represent competition for shared central resources which are  
9 limited in capacity (Huang and Mercer 2001; Woollacott and Shumway-Cook 2002). Both the variability of  
10 stride time (STV), which is an indicator of gait automaticity and stability, and trunk motion, which is an  
11 indicator of postural control and stability, are frequently used to interpret the role of cognition in the control of  
12 gait (Hausdorff 2001; IJmker and Lamothe 2012). Changes in both STV and trunk motion are used to assess fall  
13 risk and gait rehabilitation interventions in older and cognitively impaired adults (de Hoon et al 2003; Montero-  
14 Odasso et al 2012).

15  
16 The left prefrontal cortex has been implicated in the allocation of cognitive resources between two  
17 simultaneously performed tasks (Collette et al 2005) and recent evidence from studies using functional near-  
18 infrared spectroscopy has revealed that there is increased prefrontal cortex activation during DT gait (Holtzer et  
19 al 2011; Doi et al 2013). There is a growing body of research indicating that transcranial direct current  
20 stimulation (tDCS) of the prefrontal cortex influences cognitive function (Kuo and Nitsche 2012). tDCS is a  
21 non-invasive electrophysiological stimulation technique which elicits polarity dependent effects on the cortex:  
22 cortical excitability increases after anodal tDCS and decreases after cathodal tDCS (Stagg and Nitsche 2011).  
23 Only one study has used tDCS as an intervention in DT gait: Zhou and colleagues (2014) reported that  
24 prefrontal anodal tDCS with a current intensity of 1.5mA reduced the dual-task cost on gait speed and trunk  
25 motion. Anodal tDCS was thought to increase the availability of cognitive resources for task performance.  
26 However, there was no effect of prefrontal tDCS on STV or cognitive task performance. As a result, the precise  
27 role of the prefrontal cortex in the control of DT gait is not clear. During the performance of two simultaneous  
28 tasks, the prefrontal cortex is suggested to exert top-down control on task performance by biasing cognitive  
29 processing (Miller and Cohen 2001). Therefore it is possible that, rather than increasing cognitive capacity,  
30 prefrontal anodal tDCS increased the bias and allocation of cognitive resources to one aspect of DT gait  
31 performance, gait speed. If the prefrontal cortex is involved in the bias and prioritisation of aspects of task  
32 performance during DT gait, then prefrontal cathodal tDCS, which reduces cortical activity, might be expected  
33 to interfere with ongoing bias signals from the prefrontal cortex, resulting in performance decrements in one or  
34 both tasks (Vines et al 2006; Johnson et al 2007). Examining the effects of both prefrontal anodal and cathodal  
35 tDCS may thus help identify the role of the prefrontal cortex in the control of DT gait.

36  
37 The effect of tDCS on STV and cognitive task performance may also be influenced by task difficulty. DT gait  
38 performance is mediated by the relative difficulty of both the walking and cognitive task, because more difficult  
39 motor or cognitive tasks reduce the availability of shared high-level cognitive resources (Huang & Mercer 2001).  
40 STV increases during more difficult walking, indicating an increased contribution from high-level resources

41 (Hausdorff 2005; Kelly et al 2010). In the study by Zhou et al (2014), participants walked at their preferred  
42 walking speed whilst performing serial subtractions. As tDCS is suggested to influence the allocation of  
43 cognitive resources during dual-task performance (Zhou et al 2014) then the walking speed (i.e. the difficulty of  
44 the walking task) may mediate the effect of tDCS on DT gait.

45

46 The primary aim of this study was to examine the role of the prefrontal cortex in the control of DT gait using  
47 anodal and cathodal tDCS. We hypothesised that prefrontal anodal tDCS would amplify the bias of one task  
48 over the other, whilst cathodal tDCS would interfere with usual task bias during DT gait. We also hypothesised  
49 that the effects of tDCS would be mediated by walking speed.

50

51 Materials and Methods

52 Participants

53 Ten right handed males (mean  $\pm$  SD age: 23.0  $\pm$  3.2 years) volunteered to participate in the study. Handedness  
54 was assessed using the Edinburgh handedness inventory (Oldfield 1971). Informed consent was obtained from  
55 all participants included in the study. Medical contra-indications to tDCS were screened using self-completed  
56 health questionnaires. Exclusion criteria for enrolment included epilepsy, surgically implanted materials in the  
57 head or neck, known allergies to preparation materials, a history of psychiatric disease or previous neurosurgical  
58 procedures. All procedures were conducted in accordance with the declaration of Helsinki and were approved  
59 by the local University ethical committee.

60 Gait analysis

61 Temporal gait variables and trunk motion were recorded using a portable gait analysis system which consisted  
62 of three body worn sensors, each containing a triaxial accelerometer and gyroscope (OPAL, APDM, Portland,  
63 USA). Two sensors were placed on the shank of each leg, anterior and 4cm superior to the malleous process.  
64 The third sensor was placed on the lumbar spine, at section L5. The method by which temporal gait parameters  
65 are derived from angular accelerations of each shank are described in detail elsewhere (see Salarian et al. 2004).  
66 Briefly, temporal gait measures were calculated from shank angular velocity recorded by the gyroscopes on  
67 each leg (range  $\pm$  2000 °/s, sample rate 128 Hz). Stride time (s) was recorded as the time in seconds between  
68 successive heel contacts for the same leg. STV (%) was calculated as the coefficient of variation of stride time.  
69 Trunk angular distance (deg) per gait cycle in both the anterior-posterior (AP) and medio-lateral (ML) directions  
70 were integrated from the trunk and shank gyroscope data and recorded as trunk range of motion (RoM). The  
71 sensors transmitted their data online to a wireless receiver linked to a personal computer running the Mobility  
72 Lab software package (APDM, Portland, USA) where the data were filtered and underwent online bias removal.  
73 STV and trunk RoM data were analysed offline using Mobility Lab.

74 Cognitive task – serial subtraction

75 Starting from a number between 590-600, participants were required to verbally subtract in sevens for 120s. The  
76 starting number for each trial was chosen by using a pseudo-randomisation function in Microsoft Excel (Version  
77 2013, Microsoft Corporation, Redmond, USA). The number of correct responses and errors were recorded using  
78 a portable digital dictaphone (UX200, Sony, Tokyo, Japan) and analysed off-line. The ratio of errors to correct  
79 answers (error ratio) was then calculated using the following equation:

80 
$$\left( \frac{\text{Number of errors}}{\text{Number of correct answers}} \right) \times 100$$

81 Transcranial direct current stimulation

82 Transcranial stimulation was delivered via a programmable battery driven stimulator (HDCKit, Newronika,  
83 Milan, Italy). Participants received anodal, cathodal or sham tDCS in a randomised order. The stimulator was  
84 programmed by a technical member of staff not involved in the study and both participant and experimenter

85 were blind to the stimulation condition. Both active and reference rubber electrodes were placed in saline soaked  
86 sponges. The active electrode was 35cm<sup>2</sup> in size and was placed over the left prefrontal cortex at F3 using the  
87 10-20 EEG system. The reference electrode was 72cm<sup>2</sup> in size and was placed over the contralateral supra-  
88 orbital region. We chose to use a larger reference electrode to reduce current density and stimulation efficacy at  
89 this site (Nitsche et al 2008). The applied current was 1.5mA, giving a current density of 0.043mA/cm<sup>2</sup> under  
90 the active electrode and 0.021mA/cm<sup>2</sup> under the reference electrode. Current was ramped up for 15s in all  
91 conditions. For the active (anodal and cathodal) conditions, stimulation was applied for 15 minutes. For the  
92 sham condition, current was switched off after 30s (Gandiga et al 2006).

### 93 Experimental design

94 Initially, following familiarisation with experimental procedures, participants' preferred walking speed was  
95 determined. Starting at 2.0 km.h<sup>-1</sup>, participants walked on a motorised treadmill (CLST, Life Fitness,  
96 Cambridge, UK). Participants were blinded to their walking speed. Walking speed was increased in 0.1 km.h<sup>-1</sup>  
97 increments until the participant indicated that they were walking at their preferred speed. Walking speed was  
98 then increased to 6.5 km.h<sup>-1</sup> and reduced in 0.1 km.h<sup>-1</sup> increments until participants indicated that they were  
99 walking at preferred walking speed. This process was repeated and the mean of the four identified speeds was  
100 recorded as each individual's preferred walking speed.

101 Following familiarisation, each participant then participated in three testing sessions separated by at least 48  
102 hours. The protocol during each session was as follows: initially participants performed the serial subtraction  
103 task whilst standing facing a fixation point 2m in front of the treadmill. This served as the single task condition  
104 for the cognitive task. Subsequently, participants walked for 240s at both their preferred walking speed and a  
105 speed equal to 25% of preferred walking speed, in a counterbalanced order. Participants rested for 30s between  
106 each walking speed change, and walked for 30s at the new speed before data collection began. Pilot data from  
107 our laboratory (see Appendix) has shown that performing a serial subtraction task whilst walking at a speed  
108 equal to 25% of preferred walking speed is perceived as more difficult than performing the same task whilst  
109 walking at preferred walking speed. During each four minute stage, participants walked for 120s with no  
110 additional task (single task) and for 120s whilst performing the serial subtraction task (dual-task), also in a  
111 counterbalanced order. After both walking stages were completed, the participants' received tDCS whilst seated.  
112 Participants were asked to sit in silence without performing any other task during the stimulation. After  
113 stimulation cessation, the walking protocol was immediately repeated.

### 114 Data Analysis

115 All data are reported mean  $\pm$  SD. We examined the effect of tDCS and walking speed on DT gait and on the  
116 dual-task cost on STV, trunk RoM and error ratio. The dual-task cost, a measure of change from single to dual-  
117 task conditions (Kelly et al 2010), was calculated for STV and trunk RoM using the following equation:

118 
$$\left( \frac{(Dual\ task - Single\ task)}{Single\ task} \right) \times 100$$

119 Because an error ratio of zero is possible, the dual-task cost on cognitive task performance was calculated using  
120 the following equation:

121 
$$(Dual\ task - Single\ task)$$

122 The effects of stimulation and walking speed on DT gait were examined using a three way repeated measure  
123 ANOVA (stimulation condition [anodal, cathodal and sham] x walking speed [preferred, slow] x time [pre and  
124 post stimulation]). Significant effects were followed up using Bonferroni-corrected pairwise comparisons. Non-  
125 Gaussian data were normalised using logarithmic and square root transformations (Tabachnick and Fidell 2007).  
126 If data remained non-parametric after transformation, the effects of stimulation were analysed at each speed  
127 using a two way Freidman's ANOVA with Bonferroni-corrected Wilcoxon signed rank tests follow up.  
128 Statistical significance was set at  $p < 0.05$ . Partial eta squared ( $\eta p$ ) was used as a measure of effect size for main  
129 and interaction effect sizes and Cohen's  $d_{av}$  for within subjects repeated measures ( $d$ ) was used for pairwise  
130 comparison effect sizes (Lakens 2013).

131

132 Results

133 Gait Analysis

134 Participants' mean preferred walking speed was  $1.2 \pm 0.07$  m.s<sup>-1</sup>. Mean  $\pm$  SD number of strides and stride time  
135 (s) for each speed (across all three stimulation conditions and times) are presented in Table 1.

136 Table 1 here

137 The effect of tDCS on stride time variability

138 Table 2 shows the mean STV and trunk Rom during dual-task gait, and the mean dual-task cost on STV and  
139 trunk RoM. For STV during DT gait, after logarithmic transformation there was no main effect for stimulation  
140 condition ( $F_{(2,18)}=0.5$ ,  $p=0.611$ ,  $\eta p=0.053$ ) or time (pre-post) ( $F_{(1,9)}<0.1$ ,  $p=0.990$ ,  $\eta p<0.001$ ). There was an  
141 effect of walking speed on STV, where STV was higher at the slow walking speed ( $F_{(1,9)}=505.6$ ,  $p<0.001$ ,  
142  $\eta p=0.983$ ) There was a significant interaction between stimulation condition and time ( $F_{(2,18)}=5.0$ ,  $p=0.019$ ,  
143  $\eta p=0.355$ ), Figure 1). Bonferroni corrected pairwise comparisons revealed that STV decreased after anodal  
144 tDCS ( $p=0.011$ ,  $d=0.1$ ) and increased after cathodal tDCS ( $p=0.029$ ,  $d=0.2$ ). There was no difference in STV  
145 after sham tDCS ( $p=0.535$ ,  $d=0.1$ ). There was no interaction between stimulation condition, walking speed and  
146 time ( $F_{(2,18)}=1.2$ ,  $p=0.330$ ,  $\eta p=0.116$ ).

147 Figure 1 Here

148 For the dual-task cost on STV, after logarithmic transformation there was no main effect for stimulation  
149 condition ( $F_{(2,18)}=2.5$ ,  $p=0.112$ ,  $\eta p=0.216$ ), time (pre-post) ( $F_{(1,9)}=1.4$ ,  $p=0.394$ ,  $\eta p<0.001$ ) or of walking speed  
150 ( $F_{(1,9)}=0.5$ ,  $p=0.494$ ,  $\eta p=0.053$ ). There was a significant interaction between stimulation condition and time  
151 ( $F_{(2,18)}=3.8$ ,  $p=0.041$ ,  $\eta p=0.299$ , Figure 2). The dual-task cost on STV was lower after anodal stimulation  
152 ( $p=0.002$ ,  $d=0.6$ ) and there was a trend for the dual task cost on STV to be higher after cathodal tDCS ( $p=0.063$ ,  
153  $d=0.6$ ). There was no difference in the dual-task cost on STV after sham stimulation ( $p=0.765$ ,  $d=0.1$ ). Again,  
154 there was no interaction between stimulation condition, walking speed and time ( $F_{(2,18)}=0.6$ ,  $p=0.578$ ,  
155  $\eta p=0.059$ ).

156 Figure 2 here

157

158 The effect of tDCS on trunk RoM

159 For ML trunk RoM after logarithmic transformation there was no main effect for stimulation condition  
160 ( $F_{(2,18)}=0.6$ ,  $p=0.578$ ,  $\eta p=0.059$ ) or time (pre-post) ( $F_{(1,9)}<0.1$ ,  $p=0.976$ ,  $\eta p<0.001$ ). There was an effect of  
161 walking speed on ML trunk RoM where trunk RoM was lower at the slow walking speed ( $F_{(1,9)}=12.4$ ,  $p=0.006$ ,  
162  $\eta p=0.983$ ). There was no interaction between stimulation condition and time ( $F_{(2,18)}=1.6$ ,  $p=0.238$ ,  $\eta p=0.147$ )  
163 and no three way interaction between stimulation condition, time and walking speed ( $F_{(2,18)}=1.6$ ,  $p=0.225$ ,  
164  $\eta p=0.153$ ). For AP trunk RoM after logarithmic transformation there was no main effect for stimulation  
165 condition ( $F_{(2,18)}<0.1$ ,  $p=0.979$ ,  $\eta p=0.002$ ), time (pre-post) ( $F_{(1,9)}=2.9$ ,  $p=0.121$ ,  $\eta p=0.246$ ) or walking speed



166 ( $F_{(1,9)}=4.7$ ,  $p=0.059$ ,  $\eta p=0.342$ ). There was also no interaction between stimulation and time ( $F_{(2,18)}=0.6$ ,  
167  $p=0.577$ ,  $\eta p=0.059$ ) or between stimulation, time and walking speed ( $F_{(2,18)}=0.1$ ,  $p=0.949$ ,  $\eta p=0.006$ ).

168 Table 2 here

169 At the preferred walking speed, there was no interaction between stimulation and time on the dual-task cost on  
170 ML trunk RoM ( $X^2_{(5)}=1.4$ ,  $p=0.925$ ) or AP trunk RoM ( $X^2_{(5)}=8.4$ ,  $p=0.136$ ). At the slow walking speed, there  
171 was no significant interaction between stimulation condition and time on the dual-task cost on ML trunk RoM  
172 ( $X^2_{(5)}=4.8$ ,  $p=0.444$ ). There was a significant interaction between stimulation condition and time on the dual-task  
173 cost on AP trunk RoM ( $X^2_{(5)}=11.4$ ,  $p=0.042$ ) however Bonferroni corrected follow up revealed no statistically  
174 significant differences in AP trunk RoM following stimulation (all  $p>0.05$ ).

175 The effect of tDCS on cognitive task performance

176 Table 3. shows the mean  $\pm$  SD error ratio and dual-task cost on the error ratio. For error ratio during DT gait,  
177 after logarithmic transformation there was no main effect for stimulation condition ( $F_{(2,18)}=1.8$ ,  $p=0.202$ ,  
178  $\eta p=0.163$ , time (pre-post) ( $F_{(1,9)}=2.0$ ,  $p=0.194$ ,  $\eta p=0.180$ ) or walking speed ( $F_{(1,9)}=2.3$ ,  $p=0.162$ ,  $\eta p=0.205$ ).  
179 There was an interaction between stimulation condition and time ( $F_{(2,18)}=3.9$ ,  $p=0.039$ ,  $\eta p=0.302$ , Figure 3).  
180 Error ratio was lower after anodal tDCS ( $p=0.004$ ,  $d=1.1$ ). There was no difference in error ratio after cathodal  
181 tDCS ( $p=0.925$ ,  $d<0.1$ ) or sham tDCS ( $p=0.324$ ,  $d=0.4$ ). There was no interaction between stimulation  
182 condition, time and walking speed ( $F_{(2,18)}=0.9$ ,  $p=0.433$ ,  $\eta p=0.089$ ).

183 Figure 3 here

184 For the dual-task cost on error ratio, after logarithmic transformation there was no main effect for stimulation  
185 condition ( $F_{(2,18)}=1.1$ ,  $p=0.365$ ,  $\eta p=0.106$ , time (pre-post) ( $F_{(1,9)}=2.8$ ,  $p=0.128$ ,  $\eta p=0.238$ ) or walking speed  
186 ( $F_{(1,9)}=1.9$ ,  $p=0.197$ ,  $\eta p=0.177$ ). There was also an interaction between stimulation condition and time  
187 ( $F_{(2,18)}=4.1$ ,  $p=0.034$ ,  $\eta p=0.313$ , Figure 4) where the dual-task cost on error ratio was lower after anodal  
188 stimulation ( $p=0.006$ ,  $d=0.9$ ). There was no difference in the dual-task cost on error ratio after cathodal tDCS  
189 ( $p=0.939$ ,  $d<0.1$ ) or sham tDCS ( $p=0.323$ ,  $d=0.2$ ). There was no interaction between stimulation condition, time  
190 and walking speed ( $F_{(2,18)}=0.7$ ,  $p=0.523$ ,  $\eta p=0.069$ ).

191 Figure 4 here

192 Table 3. Here

193 Discussion

194 The primary aim of this study was to investigate the role of the prefrontal cortex in the control of DT gait using  
195 transcranial direct current stimulation. Our secondary aim was to see if the effects of tDCS on DT gait were  
196 mediated by walking speed. As predicted, anodal tDCS decreased both STV and the dual-task cost on STV, and  
197 increased cognitive task performance. Conversely, cathodal tDCS increased STV and there was a trend for  
198 cathodal tDCS to increase the dual-task cost on STV. These findings support the suggestion that the prefrontal  
199 cortex is involved in the bias and prioritisation of task performance during DT gait. In contrast to our  
200 predictions, the effects of tDCS on DT gait were not mediated by walking speed. These findings extend those of  
201 Zhou et al (2014) by showing that tDCS affects STV and cognitive task performance during DT gait on a  
202 treadmill and help to clarify the role of the prefrontal cortex in the control of dual-task gait.

203

204 The effect of tDCS on dual-task gait

205 In the present study, anodal tDCS reduced STV and the dual-task cost on STV and improved cognitive task  
206 performance. Conversely, cathodal tDCS increased STV and appeared to increase the dual-task cost on STV.  
207 These results support the proposal that the prefrontal cortex is involved in the bias and prioritisation of relevant  
208 task processes during DT gait. Prefrontal cortex activity increases when multiple cognitive processes compete  
209 for cognitive resources, suggesting that the prefrontal cortex is involved in the prioritisation and filtering of  
210 relevant ongoing processes to achieve task relevant goals (Miller and Cohen 2001; Milham et al 2003). During  
211 DT gait on a treadmill, healthy adults may reduce their STV (Lövdén et al 2008). A reduction in STV represents  
212 a reduction in the allocation of cognitive resources to the control of gait (Hausdorff 2005), indicating that during  
213 DT gait on a treadmill participants prioritise the allocation of cognitive resources from gait to cognitive task  
214 performance (Lövdén et al 2008). In the present study, prefrontal anodal tDCS appears to amplify this effect;  
215 further increasing the allocation of cognitive resources away from gait and toward cognitive task performance  
216 which leads to a reduced dual-task cost on STV and increased cognitive task performance. Conversely,  
217 prefrontal cathodal tDCS increased STV and there was a trend for cathodal tDCS to increase the dual-task cost  
218 on STV. It is tempting to interpret the effect of cathodal tDCS here as the opposite of the effect of anodal tDCS:  
219 that is, if a reduction in STV after anodal tDCS represents an increase in the allocation of cognitive resources  
220 away from gait, then an increase in STV may indicate that cathodal tDCS interferes with the allocation of  
221 cognitive resources away from gait toward cognitive task performance. Alternatively, as increased STV has  
222 been linked to age and disease related declines in cognitive and prefrontal cortex function (Hausdorff 2005;  
223 Allali et al 2010; Beauchet et al 2012), here prefrontal cathodal tDCS may have reduced the availability of  
224 cognitive resources during DT gait by reducing prefrontal cortex activity, which led to an increase in STV  
225 during DT gait. Although the exact mechanism by which cathodal tDCS affects dual-task gait is unclear, the  
226 differing effects of both stimulation types indicate that the prefrontal cortex is involved in the allocation of  
227 cognitive resources during dual-task gait.

228

229 In the present study, there was no effect of tDCS on trunk RoM. This may suggest that, whilst trunk RoM is  
230 affected by dual-task gait (Doi et al 2011), the prefrontal cortex is not involved in the control of trunk RoM  
231 during gait. Alternatively, it is possible these data here represent a ceiling effect in the control of trunk RoM in  
232 healthy adults. Asai et al (2013) reported age related differences in the control of trunk RoM during DT gait. It

233 is possible that in older adults or clinical populations, there may be greater involvement from high level centres  
234 such as the prefrontal cortex and tDCS of the prefrontal cortex may effect trunk RoM in these groups. However,  
235 in contrast to the present findings, Zhou et al (2014) reported that anodal tDCS improved postural sway during a  
236 standing dual-task, suggesting that tDCS may affect trunk motion in healthy young adults under some  
237 circumstances.

238

239 Anodal tDCS is suggested to have the potential to be a useful therapeutic tool for gait rehabilitation (Zhou et al  
240 2014) and there is a large and growing body of evidence linking the application of anodal tDCS to improved  
241 cognitive functions (Kuo and Nitsche 2012; Kadosh 2013). In the present study, anodal tDCS (further) reduced  
242 STV during dual-task gait. Whilst high stride variability is often linked to falls (Hausdorff 2001) very low stride  
243 variability may also increase fall risk (Brach et al 2005). Therefore, increased allocation of cognitive resources  
244 from gait to cognitive task performance, which leads to a decreased STV, could be detrimental to gait stability  
245 and increase fall risk. Therefore, the results of the present study suggest anodal tDCS may not facilitate dual-  
246 task gait, as the exploitation of stride variability maybe required for optimum gait performance (Dingwell and  
247 Cusumano 2010). Rather, the change in STV reported here only indicates that the prefrontal cortex is involved  
248 in the control of dual-task gait. Whether these effects occur during over-ground walking is unclear however, as  
249 only Zhou et al (2014) have investigated the effect of anodal tDCS on over-ground DT gait, and found no effect  
250 on STV. The relative priority of each task (gait and cognitive) during DT gait may be influenced by the walking  
251 condition (Kelly et al 2013) which may explain the disparity between the present results and those of Zhou et al  
252 (2014). In support of this suggestion, Simoni et al (2013) previously reported that older adults' dual-task gait  
253 and cognitive task performance were influenced by walking modality, and suggested that treadmill and over-  
254 ground walking may place different demands on cortical control centres. This disparity may have important  
255 implications for practitioners who use treadmills during rehabilitation in an effort to improve over-ground  
256 walking. Future studies should compare the involvement of the prefrontal cortex in the control of dual-task gait  
257 in both walking modalities.

258

259 We chose not to record stimulation sensation or detection data after each trial, in order to reduce the possibly  
260 confounding effects of drawing participants' attention to the nature of the stimulation. However, it is possible  
261 that the effects reported here may have been influenced by the participants' perceptions during stimulation. We  
262 consider this unlikely however, as the current tDCS protocol is reported to be successful in blinding participants  
263 to the nature of the stimulation condition (Gandiga et al 2006), even if there were reported differences in the  
264 sensations felt in both conditions (Russoa et al 2013). Nonetheless, future studies using tDCS to examine brain  
265 function and cognition may want to record whether participants were accurately able to discriminate between  
266 active and sham stimulations (Russoa et al 2013) in order to ensure blinding efficacy. Alternatively, a between-  
267 participant design could be used to avoid changes in awareness of stimulation sensation confounding subsequent  
268 stimulation conditions.

269

270 The influence of walking speed on the effects of tDCS on dual-task gait

271 Our second aim was to examine whether the effect of tDCS on DT gait was mediated by walking task difficulty,  
272 which we increased by reducing walking speed. Task difficulty is a known mediator of the dual-task effect

273 (Huang and Mercer 2001) however, in contrast to our hypothesis, we found that the effects of tDCS on DT gait  
274 were not influenced by walking speed. One possible explanation for this finding is that increasing walking  
275 difficulty by decreasing walking speed does not influence prefrontal cortex activity, and the changes to gait  
276 during walking at a slow speed maybe dependent on factors other than cognitive function. Under these  
277 circumstances, the effects of tDCS of the prefrontal cortex may not be mediated by walking speed.

278

#### 279 Conclusion

280 In conclusion, here we report that anodal tDCS of the left prefrontal cortex increases the allocation of cognitive  
281 resources from gait toward cognitive task performance which occurs during DT gait on a treadmill, whereas  
282 cathodal tDCS may have interfered with the allocation of cognitive resources during DT gait performance.  
283 These results indicate that the prefrontal cortex may be involved in the allocation and prioritisation of tasks  
284 during DT gait. These preliminary data also suggest that tDCS can be used to alter the ability of healthy adults  
285 to allocate cognitive resources during dual-task treadmill walking and may help to inform future research  
286 examining the effects of tDCS on fall risk and dual-task gait.

287

288 Conflict of Interest: The authors declare that they have no conflict of interest.

289

290 References

- 291 Allali G, Dubois B, Assal F, et al (2010) Frontotemporal dementia: pathology of gait? *Mov Disord* 25:731–7.  
292 doi: 10.1002/mds.22927
- 293 Al-Yahya E, Dawes H, Smith L, et al (2011) Cognitive motor interference while walking: a systematic review  
294 and meta-analysis. *Neurosci Biobehav Rev* 35:715–28. doi: 10.1016/j.neubiorev.2010.08.008
- 295 Asai T, Doi T, Hirata S, Ando H (2013) Dual tasking affects lateral trunk control in healthy younger and older  
296 adults. *Gait Posture* 38:830–836. doi: 10.1016/j.gaitpost.2013.04.005
- 297 Beauchet O, Annweiler C, Montero-Odasso M, et al (2012) Gait control: a specific subdomain of executive  
298 function? *J Neuroeng Rehabil* 9:12. doi: 10.1186/1743-0003-9-12
- 299 Brach JS, Berlin JE, VanSwearingen JM, et al (2005) Too much or too little step width variability is associated  
300 with a fall history in older persons who walk at or near normal gait speed. *J Neuroeng Rehabil* 2:21. doi:  
301 10.1186/1743-0003-2-21
- 302 Collette F, Olivier L, Van der Linden M, et al (2005) Involvement of both prefrontal and inferior parietal cortex  
303 in dual-task performance. *Brain Res Cogn Brain Res* 24:237–51. doi: 10.1016/j.cogbrainres.2005.01.023
- 304 De Hoon EW, Allum JH, Carpenter MG, et al (2003) Quantitative assessment of the stops walking while talking  
305 test in the elderly. *Arch Phys Med Rehabil* 84:838–842. doi: 10.1016/S0003-9993(02)04951-1
- 306 Dingwell JB, Cusumano JP (2010) Re-interpreting detrended fluctuation analyses of stride-to-stride variability  
307 in human walking. *Gait Posture* 32:348–53. doi: 10.1016/j.gaitpost.2010.06.004
- 308 Doi T, Asai T, Hirata S, Ando H (2011) Dual-task costs for whole trunk movement during gait. *Gait Posture*  
309 33:712–4. doi: 10.1016/j.gaitpost.2010.12.017
- 310 Doi T, Makizako H, Shimada H, et al (2013) Brain activation during dual-task walking and executive function  
311 among older adults with mild cognitive impairment: a fNIRS study. *Aging Clin Exp Res* 25:539–44. doi:  
312 10.1007/s40520-013-0119-5
- 313 Gandiga PC, Hummel FC, Cohen LG (2006) Transcranial DC stimulation (tDCS): a tool for double-blind sham-  
314 controlled clinical studies in brain stimulation. *Clin Neurophysiol* 117:845–850.
- 315 Hausdorff JM (2001) Gait variability and fall risk in community-living older adults: a 1-year prospective study.  
316 *Arch Phys Med Rehabil* 82:1050–6. doi: 10.1053/apmr.2001.24893
- 317 Hausdorff JM (2005) Gait variability: methods, modeling and meaning. *J Neuroeng Rehabil* 2:19. doi:  
318 10.1186/1743-0003-2-19
- 319 Holtzer R, Mahoney JR, Izzetoglu M, et al (2011) fNIRS study of walking and walking while talking in young  
320 and old individuals. *J Gerontol A Biol Sci Med Sci* 66:879–87. doi: 10.1093/gerona/66.8.878
- 321 Huang HJ, Mercer VS (2001) Dual-task methodology: applications in studies of cognitive and motor  
322 performance in adults and children. *Pediatr Phys Ther* 13:133–40. doi: 10.1097/00001577-200110000-  
323 00005
- 324 IJmker T, Lamoth CJC (2012) Gait and cognition: The relationship between gait stability and variability with  
325 executive function in persons with and without dementia. *Gait Posture* 35:126–130. doi:  
326 10.1016/j.gaitpost.2011.08.022

- 327 Johnson JA, Strafella AP, Zatorre RJ (2007) The role of the dorsolateral prefrontal cortex in bimodal divided  
328 attention: two transcranial magnetic stimulation studies. *J Cogn Neurosci* 19:907–20. doi:  
329 10.1162/jocn.2007.19.6.907
- 330 Kadosh RC (2013) Using transcranial electrical stimulation to enhance cognitive functions in the typical and  
331 atypical brain. *Transl Neurosci* 4:20–33. doi: 10.2478/s13380-013-0104-7
- 332 Kelly VE, Eusterbrock AJ, Shumway-Cook A (2013) Factors influencing dynamic prioritization during dual-  
333 task walking in healthy young adults. *Gait Posture* 37:131–134. doi: 10.1016/j.gaitpost.2012.05.031
- 334 Kelly VE, Janke AA, Shumway-Cook A (2010) Effects of instructed focus and task difficulty on concurrent  
335 walking and cognitive task performance in healthy young adults. *Exp Brain Res* 207:65–73. doi:  
336 10.1007/s00221-010-2429-6
- 337 Kuo M-F, Nitsche MA (2012) Effects of transcranial electrical stimulation on cognition. *Clin EEG Neurosci*  
338 43:192–9. doi: 10.1177/1550059412444975
- 339 Lakens D (2013) Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-  
340 tests and ANOVAs. *Front Psychol* 4:1–12. doi: 10.3389/fpsyg.2013.00863
- 341 Lövdén M, Schaefer S, Pohlmeier AE, Lindenberger U (2008) Walking Variability and Working-Memory Load  
342 in Aging: A Dual-Process Account Relating Cognitive Control to Motor Control Performance. *Journals*  
343 *Gerontol Ser B Psychol Sci Soc Sci* 63:121–128. doi: 10.1093/geronb/63.3.P121
- 344 Milham MP, Banich MT, Barad V (2003) Competition for priority in processing increases prefrontal cortex 's  
345 involvement in top-down control : an event-related fMRI study of the stroop task. *Cogn Brain Res*  
346 17:212–222.
- 347 Miller EK, Cohen JD (2001) An integrative theory of prefrontal cortex function. *Annu Rev Neurosci* 24:167–  
348 202. doi: 10.1146/annurev.neuro.24.1.167
- 349 Montero-Odasso M, Verghese J, Beauchet O, Hausdorff JM (2012) Gait and cognition: a complementary  
350 approach to understanding brain function and the risk of falling. *J Am Geriatr Soc* 60:2127–36. doi:  
351 10.1111/j.1532-5415.2012.04209.x
- 352 Nitsche MA, Cohen LG, Wassermann EM, et al (2008) Transcranial direct current stimulation: state of the art  
353 2008. *Brain Stimul* 1:206–23. doi: 10.1016/j.brs.2008.06.004
- 354 Oldfield RC (1971) The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*  
355 9:97–113. doi: 10.1016/0028-3932(71)90067-4
- 356 Russoa R, Wallace D, Fitzgerald PB, et al (2013) Perception of Comfort During Active and Sham Transcranial  
357 Direct Current Stimulation: A Double Blind Study. *Brain Stimul* 6:946–951. doi:  
358 10.1016/j.brs.2013.05.009
- 359 Salarian A, Russmann H, Vingerhoets FJG, et al (2004) Gait assessment in Parkinson's disease: toward an  
360 ambulatory system for long-term monitoring. *IEEE Trans Biomed Eng* 51:1434–43. doi:  
361 10.1109/TBME.2004.827933
- 362 Simoni D, Rubbieri G, Baccini M, et al (2013) Different motor tasks impact differently on cognitive  
363 performance of older persons during dual task tests. *Clin Biomech (Bristol, Avon)* 28:692–6. doi:  
364 10.1016/j.clinbiomech.2013.05.011
- 365 Stagg CJ, Nitsche MA (2011) Physiological basis of transcranial direct current stimulation. *Neuroscientist*  
366 17:37–53. doi: 10.1177/1073858410386614

- 367 Tabachnick BG, Fidell LS (2007) Using multivariate statistics (5th ed.). Allyn & Bacon/Pearson Education,  
368 Boston MA
- 369 Vines B, Schnider N, Schlaug G (2006) Testing for causality with transcranial direct current stimulation: pitch  
370 memory and the left supramarginal gyrus. *Neuroreport* 17:1047–1050. doi:  
371 10.1097/01.wnr.0000223396.05070.a2.Testing
- 372 Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: a review of an emerging  
373 area of research. *Gait Posture* 16:1–14. doi: 10.1016/S0966-6362(01)00156-4
- 374 Yogev-Seligmann G, Hausdorff JM, Giladi N (2008) The role of executive function and attention in gait. *Mov*  
375 *Disord* 23:329–42. doi: 10.1002/mds.21720
- 376 Zhou J, Hao Y, Wang Y, et al (2014) Transcranial direct current stimulation reduces the cost of performing a  
377 cognitive task on gait and postural control. *Eur J Neurosci* 39:1343–1348. doi: 10.1111/ejn.12492
- 378