Effects of transcranial direct current stimulation over the Broca's area on tongue twister production

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Running head: Effects of tDCS on tongue twister production

Keywords: speech, transcranial direct current stimulation (tDCS), Broca, tongue twister

Abstract

Purpose:

The present study aimed to explore the short-term effect of anodal tDCS on tongue twister production.

Method:

Thirty healthy native Cantonese adult speakers were randomly assigned to the anodal tDCS group or the sham tDCS group. Anodal tDCS of 2 mA was applied over the Broca's area of the brain. The stimulation lasted for 20 minutes for the anodal tDCS group and 30 seconds for the sham tDCS group. The participants were instructed to produce a list of tongue twisters before, immediately after, and four hours after tDCS.

Result:

Speech rate and response accuracy measured immediately after stimulation was significantly faster and higher, respectively, than before stimulation. Although there was no change in speech rate measured at 4 hours after stimulation, response accuracy at that time point was significantly lower than that measured immediately after stimulation. However, there were no significant differences between the anodal tDCS and sham tDCS groups in both speech rate and response accuracy.

Conclusion:

The findings revealed that a single session of anodal tDCS over the Broca's area did not significant improved speech production during tongue twister production.

Introduction

In recent years, transcranial direct current stimulation (tDCS) has been widely used as a non-invasive brain stimulation technique to modulate cognitive functions and motor behaviours in both healthy and brain-damaged individuals (Adeyemo, Simis, Macea, & Fregni, 2012; Bastani & Jaberzadeh, 2012; Flöel, 2012; Kim et al., 2010; Sparing, Dafotakis, Meister, Thirugnanasambandam, & Fink, 2008). Research have shown that tDCS can be used to modulate motor cortex excitability in a non-invasive, reversible, selective and focal way (Nitsche & Paulus, 2000).

During tDCS, a low amplitude direct current (typically between 0.5 and 2.0 mA) is transmitted through the scalp and skull to a specific cortical region via two electrodes placed on the scalp. The exact stimulation effect depends on the polarity of the current. Generally, an anodal tDCS promotes cortical excitability whereas cathodal tDCS decreases it (Nitsche & Paulus, 2000). The mechanism of acute effect during stimulation has been discussed in depth in the literature. In a nutshell, tDCS modulates brain function by inducing the neuron's resting membrane potential to depolarise or hyperpolarise. When an anodal tDCS is delivered, the electric current causes a depolarisation of the resting membrane potential, which increases neuronal excitability and allows more spontaneous neuronal cell firing. Thus, cortical excitability is promoted by anodal tDCS. On the contrary, delivery of a cathodal tDCS induces hyperpolarisation of the resting membrane potential, thus reduces spontaneous cell firing and hence decreases cortical excitability (Nitsche & Paulus, 2000). Research in healthy individuals showed that anodal tDCS enhances motor learning (Nitsche et al., 2003), verbal fluency (Cattaneo, Pisoni, & Papagno, 2011), visuomotor performance (Antal et al., 2004) and working memory (Fregni et al., 2005). On the other hand, cathodal tDCS may reduce performance in working memory task (Berryhill, Wencil, Branch Coslett, & Olson, 2010) or

may not have significant effect on a learning task (Nitsche et al., 2003).

In the domain of speech production, recent reports have highlighted the beneficial effects of anodal tDCS over Broca's area on speech performance. Cattaneo et al. (2011) investigated the effects of anodal tDCS over Broca's area on verbal fluency in ten healthy individuals, and found that the participants produced more words in phonemic and semantic fluency task following real stimulation as compared to sham stimulation. Similar anodal tDCS effects on verbal fluency were reported by Iyer et al. (2005), in which verbal fluency was found to improve significantly in the anodal tDCS group and decreased mildly in the cathodal tDCS stimulation group. Apart from verbal fluency, Holland et al. (2011) showed that anodal tDCS over the Broca's area has significant facilitative effect on picture naming in healthy individuals. Concurrent MRI also showed that the neural facilitation effect was regionally specific to the Broca's area and was positively correlated with improvement in naming responses (Holland et al., 2011). Fiori, Cipollari, Caltagirone, and Marangolo (2014) examined the effects of tDCS over the left frontal region on speech repetition and reported more accurate and faster tongue twister production during anodal stimulation as compared to pre- and post-stimulation. On the other hand, cathodal tDCS significantly reduced tongue twisters repetition accuracy and increased reaction time (Fiori et al., 2014). These findings indicated that enhancement of frontal lobe activity, including Broca's area, might have a positive effect on articulation and suggested that left frontal region play an important role in the process of speech production.

Although our present knowledge on the relationship between Broca's area and speech production is still limited, it is undeniable that Broca's area plays a role in the neural circuitry of speech production (Kent, Kent, Weismer, & Duffy, 2000). Some studies tried to explore the connection between Broca's area and speech production by examining speech production

in individuals with a brain injury (e.g. stroke) and reported Broca's area may play a crucial role in speech articulation (Hillis et al., 2004; Marangolo, Fiori, Calpagnano, et al., 2013; Marangolo, Fiori, Cipollari, et al., 2013; Marangolo et al., 2011). Hillis et al. (2004) examined the relationship between dysfunctional brain regions and speech articulation using magnetic resonance imaging (MRI) in 80 post-stroke patients. Results showed a strong association between apraxia of speech and dysfunction of Broca's area. As such, they concluded that the inferior frontal gyrus region, where the Broca's area was located, was strongly and critically involved in speech articulation. In a tDCS study, Marangolo et al. (2011) applied anodal tDCS for 20 mins over the left inferior frontal gyrus of three chronic aphasic patients while performing a speech repetition task. After five consecutive days of tDCS with concurrent language therapy, greater response accuracy was reported following the anodic stimulation. Similar positive effects on articulation were reported in another study with eight chronic patients who underwent bihemispheric stimulation over the left and right frontal regions together with concurrent speech therapy (Marangolo, Fiori, Cipollari, et al., 2013).

Fiori et al. (2014) showed that, when anodal tDCS was delivered over the Broca's area during tongue twister repetition, increased response accuracy and faster vocal reaction time were documented when compared to pre-stimulation and 1-hour post-stimulation. As an effort to explore the lasting effect of a single session of tDCS, the present study aimed to further examine the short-term effect of tDCS on a tongue twister production task. The present study would like to investigate the immediate after-effect as well as short-term effect (i.e., four hours post stimulation) of anodal tDCS on tongue twister production. Research showed that the duration of electrophysiological effects of tDCS would outlast the duration of stimulation. For example, the after-effect of 1mA tDCS lasting for 9-13 mins may last up to

90 minutes (Nitsche & Paulus, 2001; Nitsche et al., 2003; Zheng, Alsop, & Schlaug, 2011). Based on the reported literature, it could be assumed that there will be no effect of anodal tDCS on tongue twister production four hours after stimulation. Therefore, it is hypothesised that anodal tDCS over the Broca's area (F5) will enhance speech rate and response accuracy during tongue twister production and the effect will be maintained immediately after the stimulation but not at 4 hours after stimulation.

Methods

Participants

Thirty adults (10 males and 20 females) aged from 19 to 53 years (M = 27.36 years, SD = 11.26 years) with normal hearing were recruited for the study. All participants were native speakers of Cantonese with no history of speech or language pathology, brain surgery, seizure or stroke. In addition, they were free of any electrical or metallic implanted device in their body. The participants were randomly assigned to the anodal tDCS group (n = 15) or the sham group (n = 15). The research was approved by Human Research Ethics Committee of the University of Hong Kong. All the participants gave their informed consent to participate in the study.

Procedure

Delivery of tDCS

tDCS was delivered using a constant direct current stimulator (Chattanooga Ionto, Salty Lake, USA) via a pair of saline-soaked sponge electrodes (50 mm x 70 mm EasyPads, Soterix Medical Inc., New York, USA). The anodal electrode was centred over F5 based on the extended International 10-20 system for EEG electrode placement, which corresponded

best to the Broca's area (Marangolo, Fiori, Calpagnano, et al., 2013; Naeser et al., 2010). The cathodal electrode was positioned over the contralateral frontopolar cortex (Fp2 of the extended International 10-20 system for EEG electrode placement). Previous studies have reported that the use of 35 cm^2 wet sponge with a direct current of 2 mA applied over the human cortex for up to 20 minutes is considered safe (Iyer et al., 2005; Nitsche & Paulus, 2001) and has resulted in only isolated reports on injury limited to skin irritation under the sponges (Bikson, Datta, & Elwassif, 2009). Therefore, anodal tDCS was applied at 2 mA for 20 minutes in this study. For the sham tDCS group, similar to anodal tDCS, electrodes were placed on the scalp for 20 minutes but the stimulation only lasted for 30 seconds in order to trigger similar sensation on the scalp as the anodal tDCS group.

Experimental task

Twenty-one Cantonese tongue twisters of different lengths and difficulties were included as stimuli (see Appendixes 1 and 2). Tongue twisters were used instead of normal sentences because they are formed by groups of phonetically similar words purposely made difficult to articulate. These Cantonese tongue twisters were constructed by a close sequence of similar consonant sounds. Some of them also had a close sequence of similar vowel sounds and lexical tones. The production of tongue twisters involves more complex articulatory movements than normal speech, and was reported to be sensitive to potential effects of tDCS stimulation over the Broca's area (Fiori et al., 2014). The length of tongue twisters selected varied from five words/characters to 67 words/characters per tongue twister. Taking into consideration the length of the tongue twisters and the fact that retaining auditory information may increase working memory load (Chen & Cowen, 2009), the stimuli were presented visually.

The tongue twisters were presented in a random order using the E-Prime ® 2.0 Professional (Psychology Software Tools, Inc., Sharpsburg, PA, USA). Prior to the presentation of each tongue twister, a fixation cross was presented on the computer screen for two seconds to prepare the participants of the upcoming stimulus. When a tongue twister was presented, the participants were asked to read aloud the tongue twister as fast and accurately as possible. The tongue twisters remained on the screen for the duration of the tongue twister production.

After the production of first block of tongue twisters, tDCS was set up on participants' head. The 2 mA anodal tDCS lasted for 20 minutes while the sham tDCS lasted for 30 seconds. The participants were advised to sit back and relax during stimulation. Upon completion of tDCS stimulation, the participants were asked to read aloud the second block of tongue twisters. The tongue twisters used in each block were identical but randomised in a different order. Again, the participants were instructed to read aloud the tongue twisters as fast and accurately as possible. The participants also repeated the tongue twister production task 4 hours after the offset of tDCS and they were reminded not to practice the tongue twisters between sessions. Speech produced by participants was recorded using *praat* through a high-quality microphone (SM59A, Shure, USA) and a pre-amplification system (MOTU MicroBook II, Cambridge, MA, USA). A sampling frequency of 44 kHz and quantization rate of 16 bits/sample was used.

Data analysis

Speech rate and accuracy during tongue twister production before tDCS (pre-tDCS), immediately after tDCS (post-1) and 4 hours after tDCS (post-2) were obtained. Speech rate (words per second, WPS) was calculated by dividing the total number of words produced by

duration (in seconds) from onset to the offset of the participant's response. Speech rate was calculated using WPS because Cantonese words (or characters) are monosyllabic (Bauer & Benedict, 1997). Words that were produced incorrectly or produced as self-corrections were included. Speech accuracy (%) was calculated by dividing the number of words produced correctly by the total number of words in a tongue twister. Self-corrections during tongue twister production were not judged as syllables produced correctly.

Statistical analysis

A series of repeated-measures Analyses of Variance (ANOVA) were performed for speech rate and response accuracy with *time* as a within-subject factor (pre-tDCS, post-1 and post-2) and *group* as a between-subjects factor (anodal vs. sham stimulation). All 21 tongue twisters were included for analyses. A p value of 0.05 was adopted as the level of significance.

Results

The mean speech rate and response accuracy measured before stimulation (pre-tDCS), immediately after stimulation (post-1) and 4 hours after stimulation (post-2) are displayed in Figure 1. The mean and standard deviation of speech rate and response accuracy measured for each tongue twister during the three time-points are displayed in Tables 1 and 2.

Insert Figure 1 about here

Insert Tables 1 and 2 about here

Speech rate

Results showed a significant main effect for time [$F(2,24) = 38.911$, $p < 0.001$, $\eta^2 = 0.764$] and tongue twisters [$F(20,6) = 20.349$, $p = 0.001$, $\eta^2 = 0.985$]. Post-hoc pairwise comparisons with Bonferroni adjustment revealed that speech rates measured immediately after stimulation and 4 hours after stimulation were significantly faster than before stimulation; with no difference in speech rate measured immediately after stimulation and 4 hours after stimulation found. However, there were no significant differences in speech rate measured between the anodal and sham tDCS groups ($p = 0.29$).

Response accuracy

Results showed a significant main effect for time [$F(2,24) = 26.230$, $p < 0.001$, $\eta^2 = 0.686$] and tongue twisters [$F(20,6) = 8.214$, $p < 0.01$, $\eta^2 = 0.965$]. Post-hoc pairwise comparisons with Bonferroni adjustment revealed significantly higher response accuracy immediately after stimulation and response accuracy measured at 4 hours after stimulation were significantly lower than immediately after stimulation. There were no significant differences in response accuracy measured before stimulation and 4 hours after stimulation and between the anodal and sham tDCS groups ($p = 0.11$).

Discussion

It was hypothesised that speech rate and response accuracy would improve immediately after anodal tDCS and return to pre-tDCS level 4 hours after the stimulation. However, the results showed that speech rate measured immediately after both anodal and sham tDCS were significantly faster than before stimulation and the performance of anodal tDCS group was not significantly better than the sham tDCS group. At 4 hours after stimulation, speech rate maintained and did not return to pre-tDCS level. Fiori et al. (2014)

conducted a similar study to examine the modulation effect of tDCS during tongue twister repetition. Fiori and colleague (2014) provided auditory stimuli to their participants and recorded their vocal reaction time and response accuracy during tongue twister repetition one hour before stimulation, during stimulation and one hour after stimulation was completed. Fiori et al. (2014) reported significantly faster vocal reaction time and higher response accuracy during anodal tDCS stimulation when compared to pre- and post-stimulation. Yet, the sham group did not show significant changes in both vocal reaction time and response accuracy in the three time periods.

The present findings are somewhat different from Fiori et al. (2014). It may be due to the differences in methodologies employed in the studies, including the methods of stimulus presentation (visually vs auditory); the behavioural tasks (reading aloud vs repetition), timing of data collection in relation to stimulation (pre-stimulation, immediately and 4 hours after stimulation vs. 1 hour before stimulation, during stimulation and 1 hour after stimulation); as well as the type of outcome measures used (speech rate vs vocal reaction time). The present study opted to present the tongue twisters as visual stimuli for a reading aloud task after considering the possibility of increased working memory load in retaining verbal stimuli for a repetition task as well as considering the length of stimuli up to 67 words/characters per tongue twister. The time at which data were collected also varied between the studies. Fiori et al. (2014) aimed to explore the modulation effects of anodal, cathodal and sham tDCS on speech repetition. Based on the reported modulation effects of tDCS, the present study further investigated the immediate after effect (immediately after stimulation) as well as short-term effects (4 hours after stimulation) of tDCS on speech performance. In Fiori et al. (2014), vocal reaction time was defined as the duration between offset of auditory stimulus to the offset of the participants' response, which also took into account the duration of the

participants' response. A reduction in vocal response time in their study may have been contributed by the increased speech rate during anodal tDCS. The present findings show that speech rate measured immediately after stimulation were significantly faster than before stimulation, and these phenomena were observed in both the anodal and sham tDCS groups. It was noted that Fiori et al. (2014) reported no significant changes in vocal reaction time measured in the sham group in the three time periods.

Practice effects may have played an important role in masking the effects of anodal tDCS in the study. The present study used the same list of tongue twisters for all three measurements. Although the tongue twisters were randomized and resulted in different orders for each measurement, practice effect could not be ruled out. The contribution of practice effect was more apparent when examining the mean speech rate for the sham tDCS group where there was a more obvious trend of increasing speech rate from pre-tDCS to post-1 and post-2 measurements despite there should be no stimulation effects. Additionally the participants involved in the present study (mean age = 27 years) are relatively younger than those involved in Fiori et al. (2014) with a mean age of 57. According to Pascual-Leone et al. (2011), brain plasticity was important in acquisition of new skills and the efficiency of neuronal plasticity declined throughout the age-span. To put it another way, efficiency of learning may decline with age. As the present study involved a younger group of participants, thus the practice effects may be larger resulting in a better performance in post-2 measurement than expected.

The findings also revealed significantly higher response accuracy immediately after tDCS stimulation compared to before stimulation and 4 hours after stimulation. This finding was consistent with Fiori et al. (2014) which reported an increased response accuracy after anodal tDCS stimulation. Although there were no significant differences between the anodal

and sham tDCS groups, anodal tDCS group was observed to have a higher gain in response accuracy immediately after stimulation.

Limitations and future direction

The findings from the present study should be interpreted cautiously. As mentioned previously, practice effect may be present in the study that could mask the effects of tDCS. Future studies may use three different lists of tongue twisters with similar difficulties for pre-tDCS, post-1 and post-2 measurements. In addition, the present study only involved healthy individuals as participants and the possibility of translating the results into population with speech pathology (e.g. dysarthria) is still unknown. Further studies are encouraged to examine if multiple sessions of anodal tDCS may achieve persistent beneficial effects to enhance speech production. A few studies evaluated the potential of multiple sessions of anodal tDCS in facilitating language and speech recovery in individuals with stroke. It was reported that, when paired with conventional therapy, positive effects up to two months after stimulation were documented (Fridriksson, Richardson, Baker, & Rorden, 2011; Marangolo, Fiori, Calpagnano, et al., 2013; Marangolo, Fiori, Cipollari, et al., 2013; Marangolo et al., 2011). The sustainable effects of tDCS indicating the modulatory mechanism of tDCS may not be solely attributed to changes in neuronal electrical potential of neuronal membrane. It was proposed the sustainable effect of tDCS may be explained by neuroplasticity, which refers to the ability of the neural pathways and synapses in brain to change throughout life based on changes in behaviour, environment, neural processes, thinking and emotions (Pascual-Leone et al., 2011). The effect of tDCS is hypothesised to be similar to those observed in long-term potentiation (LTP) and long term depression (LTD). LTP refers to the strengthening between two neurons through an alteration of synaptic transmission ability whereas LTD refers to the weakening between two neurons. Fritsch et al. (2010) showed that

anodal tDCS of the motor cortex induced a lasting increase in postsynaptic excitatory potentials in animals, which was similar to that in LTP. Nonetheless, our present knowledge about how tDCS promotes neuronal plasticity is limited. The actual mechanism of tDCS still remains to be fully elucidated (Brunoni et al., 2012).

Conclusions

The present study documented that a single session of anodal tDCS over the Broca's area failed to yield improved speech rate and response accuracy during tongue twisters production in healthy individuals.

Declaration of interest

The authors report no conflicts of interest.

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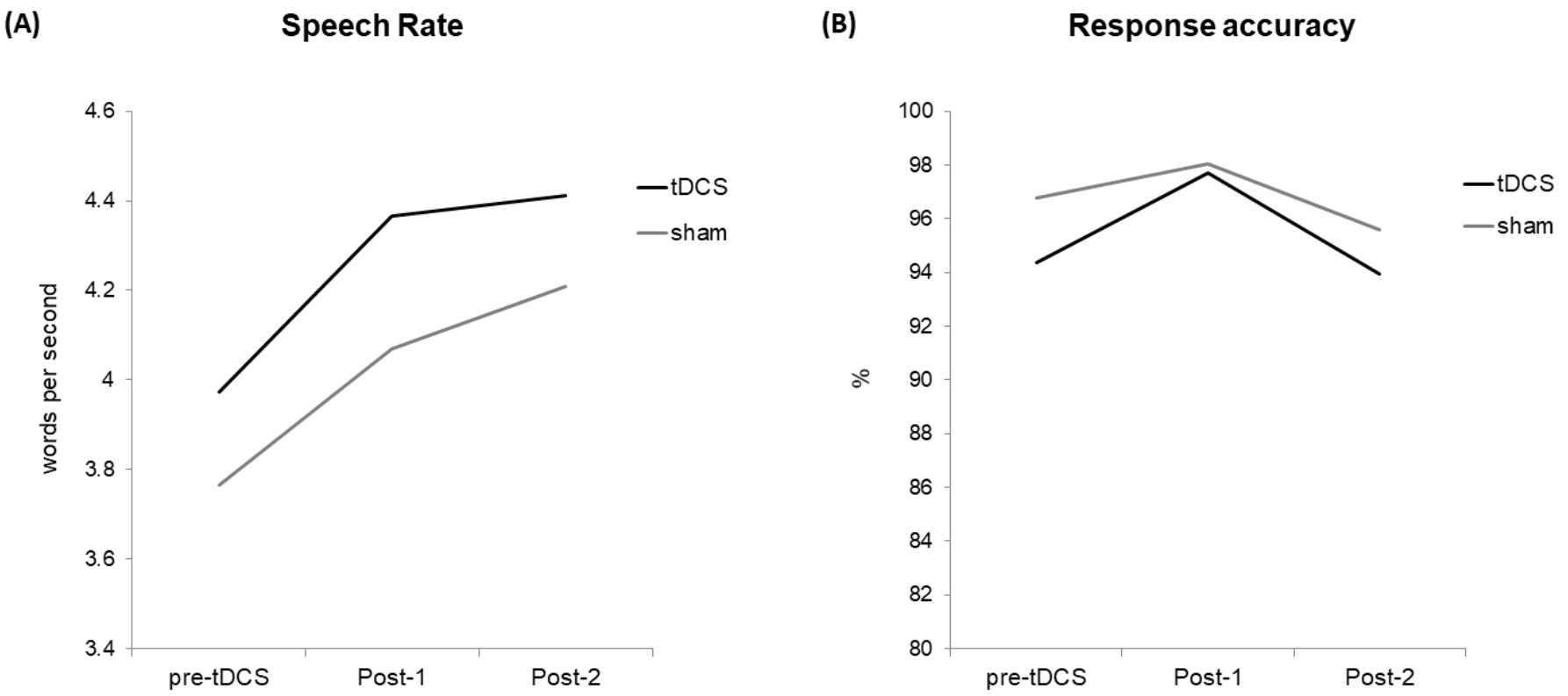
Table 1. Mean (and standard deviation) speech rate (words per second) measured for anodal and sham tDCS groups before stimulation (pre), immediately after stimulation (post-1) and at 4 hours after stimulation (post-2).

	Anodal tDCS (n = 15)			Sham tDCS (n = 15)		
Tongue	Pre	Post-1	Post-2	Pre	Post-1	Post-2
twisters	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
1	3.98(0.71)	4.47(0.78)	4.64(0.83)	3.68(0.79)	4.24(0.85)	4.17(0.86)
2	2.82(0.83)	3.26(1.02)	3.04(0.68)	2.58(0.69)	2.69(0.75)	2.75(0.80)
3	5.51(1.37)	5.52(0.99)	5.76(1.13)	4.72(0.83)	5.26(1.06)	5.40(0.85)
4	4.03(0.60)	4.50(0.72)	4.49(0.82)	3.94(0.76)	4.33(0.78)	4.68(1.50)
5	2.82(0.66)	3.22(0.63)	3.16(0.79)	2.83(0.57)	3.03(0.59)	3.02(0.69)
6	3.66(0.84)	3.88(0.97)	4.05(1.08)	3.13(0.50)	3.66(0.62)	3.85(0.42)
7	4.23(0.82)	4.70(0.70)	4.66(0.79)	3.96(0.68)	4.01(0.80)	4.53(0.71)
8	4.59(0.73)	4.90(0.89)	5.04(1.03)	4.50(0.78)	4.72(0.53)	4.87(0.54)
9	4.90(1.01)	5.40(0.81)	5.66(0.90)	4.84(0.96)	5.18(1.09)	5.49(1.03)
10	4.32(0.93)	4.84(1.04)	4.84(0.95)	4.12(0.74)	4.47(0.84)	4.62(0.87)
11	4.44(1.04)	4.36(0.89)	4.62(1.03)	3.62(0.72)	4.00(0.90)	4.24(0.95)
12	3.30(0.90)	4.02(0.91)	3.86(0.85)	3.13(0.73)	3.56(0.64)	3.51(0.67)
13	5.40(0.92)	6.02(0.96)	6.18(1.17)	5.22(1.25)	5.75(0.97)	6.25(0.96)
14	4.24(0.61)	4.70(0.81)	4.85(0.86)	4.10(0.72)	4.24(0.74)	4.66(0.79)
15	3.45(0.64)	3.93(0.86)	3.98(0.78)	3.28(0.36)	3.60(0.45)	3.75(0.43)
16	4.12(1.15)	4.56(1.23)	4.56(1.13)	4.35(1.02)	4.25(0.86)	4.04(1.02)
17	4.24(1.04)	4.62(1.10)	4.58(0.95)	4.22(0.98)	4.52(1.00)	4.78(1.53)
18	2.23(0.73)	2.67(0.64)	2.40(0.42)	2.20(0.43)	2.36(0.41)	2.53(0.47)
19	4.02(1.16)	4.52(1.12)	4.40(0.83)	4.20(1.24)	4.27(1.10)	3.95(1.10)
20	3.94(0.83)	4.10(0.77)	4.17(0.69)	3.77(0.58)	4.10(1.03)	4.03(0.59)
21	3.19(0.92)	3.45(0.70)	3.71(0.58)	2.69(0.48)	3.23(0.56)	3.25(0.57)

Table 2. Mean (and standard deviation) response accuracy (%) measured for anodal and sham tDCS groups before stimulation (pre), immediately after stimulation (post-1) and at 4 hours after stimulation (post-2).

	Anodal tDCS (n = 15)			Sham tDCS (n = 15)		
Tongue twisters	Pre	Post-1	Post-2	Pre	Post-1	Post-2
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
1	98.38(2.29)	97.37(2.15)	98.38(2.53)	97.18(3.00)	98.31(2.22)	97.18(2.82)
2	83.03(7.02)	77.34(9.72)	81.01(7.62)	87.27(10.85)	93.79(12.26)	89.44(11.15)
3	98.08(2.77)	99.18(1.57)	99.18(1.57)	100.00(0.00)	98.87(2.53)	99.49(1.30)
4	97.77(1.81)	98.38(2.02)	98.38(3.14)	98.50(1.70)	98.87(1.70)	98.50(2.87)
5	88.46(6.86)	93.68(6.21)	92.86(5.26)	97.19(3.19)	96.43(4.65)	98.21(2.71)
6	93.27(8.25)	97.12(5.48)	94.23(8.25)	97.32(5.32)	96.43(7.64)	93.75(11.76)
7	97.90(2.53)	99.30(1.43)	98.60(1.98)	98.38(2.59)	97.56(3.73)	99.51(0.97)
8	99.11(2.30)	99.70(1.07)	100.00(0.00)	99.45(1.40)	99.73(1.03)	99.73(1.03)
9	94.33(5.87)	98.38(2.53)	98.38(3.32)	98.50(3.22)	97.74(5.73)	100.00(0.00)
10	98.66(2.74)	99.67(1.21)	98.66(2.74)	99.07(2.52)	97.83(2.26)	99.07(1.85)
11	95.19(9.60)	98.08(4.69)	93.27(8.25)	95.54(9.31)	94.64(11.72)	95.54(10.52)
12	95.55(3.29)	97.37(3.56)	96.76(3.75)	96.99(2.89)	97.56(2.41)	97.93(2.57)
13	99.47(1.29)	98.67(2.24)	99.20(2.07)	98.77(1.71)	99.01(1.62)	99.01(2.11)
14	96.45(1.67)	97.63(2.21)	97.63(1.64)	97.07(2.99)	97.25(2.35)	97.99(2.29)
15	97.24(2.78)	95.06(6.31)	96.33(3.69)	96.91(2.52)	97.23(3.14)	97.23(3.20)
16	93.59(7.72)	88.78(14.96)	91.67(11.79)	91.67(10.84)	88.69(10.65)	91.07(8.93)
17	97.16(4.20)	97.83(2.17)	98.33(2.83)	98.60(1.62)	98.60(1.83)	98.60(1.83)
18	86.15(20.63)	89.23(15.53)	84.62(20.25)	94.29(9.38)	95.71(16.04)	95.71(8.52)
19	94.67(5.78)	94.67 (7.94)	97.63(3.70)	95.60(3.95)	96.70(4.97)	94.51(8.76)
20	96.48(2.89)	94.29(4.04)	96.70(2.29)	96.33(3.79)	96.33(4.81)	97.14(4.88)
21	91.51(7.44)	94.23(4.35)	96.31(5.46)	93.45(4.89)	96.13(3.04)	96.58(3.80)


(A)
Speech Rate
words per second
4.6
4.4
4.2
4
3.8
3.6
3.4
pre-tDCS
Post-1
Post-2
tDCS
sham
(B)
Response accuracy
%
100
98
96
94
92
90
88
86
84
82
80
pre-tDCS
Post-1
Post-2
tDCS
sham

Appendix 1
List of tongue twisters (with jyutping)

1 入實驗室拎緊急掣。

jɐp9 sɐt9 jim6 sɐt7 kɐm6 kɐn2 kɐp7 tsɐi3

2 郵差叔叔送信純熟迅速送出。

jɐu4 tsʰai1 sɔk7 sɔk7 sɔŋ3 sən3 sən4 sɔk9 sən3 tsʰɔk7 sɔŋ3 tsʰɵt7

3 去街市買魚腸，見到姨丈，放低魚腸，問候姨丈，執翻魚腸，拜拜姨丈。

hɵy3 kai1 si5 mai5 jy4 tsʰœŋ2, kin3 dou2 ji4 tsœŋ2, fɔŋ3 tɐi1 jy4 tsʰœŋ2, mɐn6 hɐu6 ji4 tsœŋ2, tsɐp7 fan1 jy4 tsʰœŋ2, pai1 pai3 ji4 tsœŋ2

4 掘柑掘桔掘金桔，掘雞掘骨掘龜骨，掘完雞骨掘金桔，掘完龜骨掘雞骨。

kʷɐt9 kɐm1 kʷɐt9 kɐt7 kʷɐt9 kɐm1 kɐt7, kʷɐt9 kɐi1 kʷɐt9 kʷɐt7 kʷɐt9 kʷɐi1 kʷɐt7, kʷɐt9 jyn4 kɐi1 kʷɐt7 kʷɐt9 kɐm1 kɐt7, kʷɐt9 jyn4 kʷɐi1 kʷɐt7 kʷɐt9 kɐi1 kʷɐt7

5 床腳撞牆角，牆角撞床腳，你話床腳撞牆角定牆角撞床腳？

tsʰɔŋ4 kœk8 tsɔŋ6 tsʰœŋ4 kɔk8, tsʰœŋ4 kɔk8 tsɔŋ6 tsʰɔŋ4 kœk8, nei5 wa6 tsʰɔŋ4 kœk8 tsɔŋ6 tsʰœŋ4 kɔk8 tɪŋ6 tsʰœŋ4 kɔk8 tsɔŋ6 tsʰɔŋ4 kœk8

6 一蚊一斤龜，七蚊一斤雞，佢話龜貴過雞，我話雞貴過龜，咁究竟龜貴過雞定係雞貴過龜。

jɐt7 mɐn1 jɐt7 kɐn1 kʷɐi1, tsʰɐt7 mɐn1 jɐt7 kɐn1 kɐi1, kʰɵy5 wa6 kʷɐi1 kʷɐi3 kʷɔ3 kɐi1, ŋɔ5 wa6 kɐi1 kʷɐi3 kʷɔ3 kʷɐi1, kɐm2 kɐu3 kɪŋ2 kʷɐi1 kʷɐi3 kʷɔ3 kɐi1 tɪŋ6 hɐi6 kɐi1 kʷɐi3 kʷɔ3 kʷɐi1

7 蘦線蜘蛛啲蜘蛛絲蘦住枝樹枝。

tsʰi1 sin3 tsi1 tsy1 ti1 tsi1 tsy1 si1 tsʰi1 tsy6 tsi1 sy6 tsi1

8 雞龜骨滾羹。

kɐi1 kʷɐi1 kʷɐt1 kʷɐn2 kɐŋ1

9 獅子山上獅山寺，山寺門前四獅子。山寺是禪寺，獅子是石獅。獅子看守獅山寺，禪寺保護石獅子。

si1 tsi2 san1 sœŋ6 si1 san1 tsi2, san1 tsi2 mun4 tsʰin4 sei3 si1 tsi2 / san1 tsi2 si6 sim4 tsi2, si1 tsi2 si6 sɛk9 si1 / si1 tsi2 hɔn1 sɐu2 si1 san1 tsi2, sim4 tsi2 pou2 wu6 sɛk9 si1 tsi2

10 姨媽而家去宜家家俬買而家啱用嘅宜家家俬。

ji4 ma1 ji4 ka1 hɐy3 ji4 ka1 ka1 si1 mai5 ji4 ka1 am1 jʊŋ6 kɛ3 ji4 ka1 ka1 si1

11 街頭男人難忍爛飲。

kai1 tʰɐu4 nam4 jɐn2 nan4 jɐn2 lan6 jɐm2

12 白石塔，白石搭。白石搭白塔，白塔白石搭。白石白又滑，搬來白石搭白塔，白石搭白塔，白塔白石搭，搭好白石塔，白塔白又滑。

pak9 sɛk9 tʰap8, pak9 sɛk9 tap8 / pak9 sɛk9 tap8 pak9 tʰap8, pak9 tʰap8 pak9 sɛk9 tap8 / pak9 sɛk9 pak9 jɐu6 wat9, pun1 lɔi4 pak9 sɛk9 tap8 pak9 tʰap8, pak9 sɛk9 tap8 pak9 tʰap8, pak9 tʰap8 pak9 sɛk9 tap8, tap8 hou2 pak9 sɛk9 tʰap8, pak9 tʰap8 pak9 jɐu6 wat9

13 一隻馬騮仔帶一群馬騮仔去溝仔，一群馬騮仔跌落溝渠底，一隻馬騮仔轉去拎鈎仔，來釣馬騮仔。

jɐt7 tsɛk8 ma5 lɐu1 tsɐi2 tai3 jɐt7 kʷʰɐn4 ma5 lɐu1 tsɐi2 hɐy3 kʰɐu1 tsɐi2, jɐt7 kʷʰɐn4 ma5 lɐu1 tsɐi2 tit8 lɔk9 kʰɐu1 kʰɵy4 tɐi2, jɐt7 tsɛk8 ma5 lɐu1 tsɐi2 tsyn3 hɐy3 lɪŋ1 ɐu1 tsɐi2, lɔi4 tiu3 ma5 lɐu1 tsɐi2

14 蔣家羊，楊家牆，蔣家羊撞倒了楊家牆，楊家牆壓死了蔣家羊，楊家要蔣家賠

牆，蔣家要楊家賠羊。

tsœŋ2 ka1 jœŋ4, jœŋ4 ka1 tsʰœŋ4, tsœŋ2 ka1 jœŋ4 tsɔŋ6 tou2 liu5 jœŋ4 ka1 tsʰœŋ4, jœŋ4 ka1 tsʰœŋ4 at8 sei2 liu5 tsœŋ2 ka1 jœŋ4, jœŋ4 ka1 jiu3 tsœŋ2 ka1 pʰui4 tsʰœŋ4, tsœŋ2 ka1 jiu3 jœŋ4 ka1 pʰui4 jœŋ4

15 東家有隻羊，中家有棟牆，東家隻羊撞到中家棟牆，中家棟牆撞死東家隻羊，中家要東家賠羊，東家要中家賠牆。

tʊŋ1 ka1 jɐu5 tsɛk8 jœŋ4, tsʊŋ1 ka1 jɐu5 tʊŋ6 tsʰœŋ4, tʊŋ1 ka1 tsɛk8 jœŋ4 tsɔŋ6 tou2 tsʊŋ1 ka1 tʊŋ6 tsʰœŋ4, tsʊŋ1 ka1 tʊŋ6 tsʰœŋ4 tsɔŋ6 sei2 tʊŋ1 ka1 tsɛk8 jœŋ4, tsʊŋ1 ka1 jiu3 tʊŋ1 ka1 pʰui4 jœŋ4, tʊŋ1 ka1 jiu3 tsʊŋ1 ka1 pʰui4 tsʰœŋ4

16 雙層牛肉巨無霸，醬汁洋蔥夾青瓜，芝士生菜加芝麻，人人食到笑哈哈！

sœŋ1 tsʰɐŋ4 ŋɐu4 jʊk9 kɵy6 mou4 pa3, tsœŋ3 tsɐp7 jœŋ4 tsʰʊŋ kɛp9 tsʰɛŋ kʷa1, tsi1 si2 saŋ1 tsʰɔi3 ka1 tsi1 ma4, jɐn4 jɐn4 sɪk9 tou3 siu3 ha1 ha1

17 麥當娜約咗麥當雄去麥當勞道嗰間麥當勞食麥皮撈當歸 。

mɐk9 tɔŋ1 na4 jœk8 tsɔ2 mɐk9 tɔŋ1 hʊŋ4 hɵy3 mɐk9 tɔŋ1 lou3 tou6 kɔ2 kan1 mɐk9 tɔŋ1 lou3 sɪk9 mɐk9 pʰei4 lou1 tɔŋ1 kʷɐi1

18 肯德龜同肯德雞去肯德基食肯德基最出名嘅巴辣香雞 。

hɐŋ2 tɐk7 kʷɐi1 tʰʊŋ4 hɐŋ2 tɐk7 kɐi1 hɵy3 hɐŋ2 tɐk7 kei1 sɪk9 hɐŋ2 tɐk7 kei1 tsɵy3 tsʰɵt7 mɛŋ2 kɛ3 pa1 lat9 hœŋ1 kɐi1

19 郭藹明見過郭可盈，話郭可盈個袋型，郭可盈叫郭藹明過海改個袋型，改成郭可盈個袋個袋型。

kʷɔk8 ɔi2 mɪŋ4 kin3 kʷɔ3 kʷɔk8 hɔ2 jɪŋ4, wa6 kʷɔk8 hɔ2 jɪŋ4 kɔ3 tɔi2 jɪŋ4, kʷɔk8 hɔ2 jɪŋ4 kiu3 kʷɔk8 ɔi2 mɪŋ4 kʷɔ3 hɔi2 kɔi2 kɔ3 tɔi2 jɪŋ4, kɔi2 sɪŋ4 kʷɔk8 hɔ2 jɪŋ4 kɔ3 tɔi2 kɔ3 tɔi2 jɪŋ4

20 東門東家，南門董家。 東董兩家，同種冬瓜。有人說：東門東家的冬瓜大。誰知南門董家的冬瓜大過東門東家的大冬瓜。

tʊŋ1 mun4 tʊŋ1 ka1, nam4 mun4 tʊŋ2 ka1 / tʊŋ1 tʊŋ2 lœŋ5 ka1, t^{h}ʊŋ tsʊŋ3 tʊŋ1 k^{w}a1 / jɐu5 jɐn4 syt8：tʊŋ1 mun4 tʊŋ1 ka1 tɪk1 tʊŋ1 k^{w}a1 tai6 / sɵy4 tsi1 nam4 mun4 tʊŋ2 ka1 tɪk7 tʊŋ1 k^{w}a1 tai6 k^{w}ɔ3 tʊŋ1 mun4 tʊŋ1 ka1 tɪk7 tai6 tʊŋ1 k^{w}a1

21 圓圓遠遠叫圓月，叫來圓月來賞月。圓圓說：月月圓，圓月說：圓圓月。圓圓說：圓月的眼圓比月圓。 圓月說：圓圓的圓眼賽圓月。究竟是圓圓，圓月的眼兒圓，還是圓圓的月兒圓。

jyn4 jyn4 jyn5 jyn5 kiu3 jyn4 jyt9, kiu3 lɔi4 jyn4 jyt9 lɔi4 sœŋ2 jyt2 / jyn4 jyn4 syt8：jyt9 jyt9 jyn4, jyn4 jyt9 syt8：jyn4 jyn4 jyt9 / jyn4 jyt4 syt8：jyn4 jyt9 tɪk7 ŋan5 jyn4 pei2 jyt9 jyn4 / jyn4 jyt9 syt8：jyn4 jyn4 tɪk7 jyn4 ŋan5 ts^{h}ɔi jyn4 jyt9 / kɐu3 kɪŋ2 si6 jyn4 jyn4, jyn4 jyt6 tɪk7 ŋan5 ji4 jyn4, wan4 si6 jyn4 jyn4 tɪk7 jyt9 ji4 jyn4

Appendix 2
List of tongue twisters (with translations)

1 入 實驗室 扮 緊急 掣。

Enter laboratory press emergency button

Go into the laboratory and press the emergency button.

2 郵差 叔叔 送 信 純熟 迅速 送 出。

Postman uncle delivers mail skilfully swiftly delivers out

The postman delivers mail swiftly.

3 去 街市 買 魚腸， 見到 姨丈，放 低 魚腸，

Go to market buy fish intestines see uncle put down fish intestines

問候 姨丈， 執翻 魚腸， 拜拜 姨丈。

greet uncle pick up fish intestines bye uncle

(He) went to the market to buy fish intestines. (He) saw his uncle, greeted him, picked up the fish intestines, and said goodbye to him.

4 掘 柑 掘 桔 掘 金桔，掘 雞 掘 骨 掘 龜骨， 掘

Dig orange dig tangerine dig kumquat dig chicken dig bone dig tortoise bone dig

完 雞骨 掘 金桔，掘 完 龜骨 掘 雞骨。

finish chicken bone dig kumquat dig finish tortoise bone dig chicken bone

Dig the orange, dig the tangerine, dig the kumquat. Dig the chicken, dig the bone, dig the tortoise shell. After digging the chicken bone, dig the kumquat. After digging the tortoise shell, dig the chicken bone.

5 床腳 撞 牆角， 牆角 撞 床腳，你 話 床腳 撞

Foot of bed hit corner of wall corner of wall hit foot of bed you say foot of bed hit

牆角　　定　　牆角　　撞　　床腳?

corner of wall or corner of wall hit foot of bed

A foot of a bed hits a corner, vice versa. Do you think the foot of the bed hit the corner or the corner hit the foot of the bed?

6　一　蚊　一　斤　龜，　七　蚊　一　斤　雞，　佢　話　龜

One dollar one catty tortoise seven dollar one catty chicken he/she say tortoise

貴過　　雞，我 話　雞　　貴過　　龜，　咁究竟

more expensive than chicken I say chicken more expensive than tortoise　so

龜　　貴過　　雞　定係 雞　　貴過　　龜。

tortoise more expensive than chicken or chicken more expensive than tortoise

A catty of tortoise costs a dollar, while a catty of chicken costs seven dollars. He says that the tortoise is more expensive than the chicken, while I say that the chicken is more expensive than the tortoise. So, which one is more expensive, chicken or tortoise?

7　蠔線　蜘蛛　啲 蜘蛛絲　蠔 住枝 樹枝。

Crazy spider’s cobweb stick to a branch

A crazy spider’s cobweb is stuck to a branch.

8　雞　　龜　　骨　滾　羹。

Chicken tortoise bone boil soup

Cook soup with chicken and tortoise bones.

9　獅子山　上　　獅山寺，　　山寺　　門　　前　　四 獅子。

Lion Hill on Lion Hill Temple mountain temple door in front of four lion

山寺　　是　　禪寺，　獅子是　石獅。獅子看守　　獅山寺，

mountain temple is Buddhist temple lion is stone lion lion guard Lion Hill Temple

禪寺　　保護　石獅子。

Buddhist temple protect stone lion

On Lion Hill stands Lion Hill Temple, in front of the entrance of the mountain temple are four lions. The mountain temple is a Buddhist temple, while the lions are stone lions. The lions guard Lion Hill Temple, while the Buddhist temple protects the stone lions.

10　姨媽 而家去 宜家家俬 買　而家 啱用　嘅　宜家家俬。

Aunt now go　Ikea　buy now suitable’s Ikea furniture

Aunt is now off to Ikea to buy Ikea furniture that is/are suitable for use now.

11　街頭 男人　　難忍　　爛飲。

Street man cannot refrain from binge drinking

The man on the street cannot refrain himself from binge drinking.

12　白　石　塔，白　石　搭。白　石　搭　白　塔，白　塔　白

White stone tower white stone build white stone build white tower white tower white

石　搭。白　石　白　又　滑，　搬 來 白　石　搭　白　塔，

stone build white stone white and smooth move to white stone build white tower

白　石　搭　白　塔，白　塔　白　石　搭，搭　好　白　石

white stone build white tower white tower white stone build build finish white stone

塔，　白　塔　白　又　滑。

tower white tower white and smooth

White stones are used to build a white stone tower. Build the white tower with white stones. The white stones are white and smooth. Bring white stones to build the white

tower. Build the white tower with white stones. Upon the completion of the construction of the white stone tower, the tower is white and smooth.

13 一隻馬騮仔 帶 一群 馬騮仔 去 溝仔， 一群 馬騮仔 跌 落 溝渠

A monkey bring a group of monkeys to ditch a group of monkeys fall down ditch

底， 一隻馬騮仔 轉去 拎 鈎仔，來 釣 馬騮仔。

bottom a monkey turn to take hook to fish monkeys

A monkey brought a group of monkeys to a ditch. A group of monkeys fell down to the bottom of the ditch. A monkey went to take a hook to fish for the monkeys.

14 蔣家 羊，楊家 牆，蔣家 羊 撞倒了 楊家 牆，楊家 牆 壓死了蔣家

Jiang sheep Yang wall Jiang sheep knock down Yang wall Yang wall crushed Jiang

羊， 楊家 要 蔣家 賠 牆，蔣家 要 楊家 賠 羊。

sheep Yang ask Jiang compensate wall Jiang ask Yang compensate sheep

Jiang had a sheep and Yang had a wall. Jiang’s sheep knocked down Yang’s wall, and Yang’s wall crushed Jiang’s sheep to death. Yang asked Jiang to compensate for the wall, while Jiang asked Yang to compensate for the sheep.

15 東家 有 隻 羊， 中家 有 棟 牆，東家 隻 羊 撞到中家 棟牆， 中家 棟

Dungs has a sheep Zhungs has a wall Dungs’ sheep hit Zhungs’ wall Zhungs’

牆 撞 死 東家 隻羊，中家 要 東家 賠 羊，東家 要 中家

wall hit die Dungs’ sheep Zhungs ask Dungs compensate sheep Dungs ask Zhungs

賠 牆。

compensate wall

Dungs has a sheep and Zhungs has a wall. Dungs’ sheep hit Zhungs’ wall and died.

The Zhungs asked The Dungs to compensate for the sheep, while the Dungs asked the Zhungs to compensate for the wall.

16 雙層 牛肉 巨無霸，醬汁 洋蔥 夾 青瓜， 芝士 生菜 加

Double layer beef Big Mac sauce onion with cucumber cheese lettuce plus

芝麻， 人人 食 到笑哈哈！

sesame seeds everybody eat till laugh

Big Mac with two beef patties, sauce, onion, cucumber, cheese, lettuce, and sesame seeds. Everybody eats it happily.

17 麥當娜 約咗 麥當雄 去 麥當勞道 嗰間 麥當勞 食

Madonna asked out Mak Dong Hung to MacDonnell Road that McDonald’s eat

麥皮 撈 當歸。

oatmeal mix Angelica

Madonna asked Mak Dong Hung on a date to the McDonald’s on MacDonnell Road to eat oatmeal mixed with Angelica.

18 肯德 龜 同 肯德雞 去肯德基 食肯德基 最 出名 嘅

Kentucky tortoise and KFC chicken go KFC eat KFC most famous’s

巴辣香雞。

hot and spicy chicken

Kentucky tortoise and KFC chicken go to KFC for its most famous hot and spicy chicken.

19 郭藹明 見過 郭可盈， 話 郭可盈 個 袋 型， 郭可盈

Kwok Oi Ming met Kwok Ho Ying say Kwok Ho Ying’s bag cool Kwok Ho Ying

叫　郭藹明　過海　改 個 袋 型，改 成

tell Kwok Oi Ming cross the harbour change the bag shape change to

郭可盈　個 袋 個 袋 型。

Kwok Ho Ying’s bag’s bag shape

Kwok Oi Ming met Kwok Ho Ying and said that her bag is cool. Kwok Ho Ying told her to cross the harbour to change the shape of her bag to her own bag’s shape.

20 東 門 東家，南 門 董家。東 董 兩 家，同 種

East gate the Dungs south gate the Dungs Dungs Dungs two family same grow

冬瓜。有人 說：東 門 東家 的 冬瓜 大。誰 知

white gourd someone say east gate the Dungs’ white gourd big who knows

南 門 董家 的 冬瓜 大 過 東 門 東家 的 大

south gate the Dungs’ white gourd bigger than east gate the Dungs’ big

冬瓜。

white gourd

The Dungs living in the eastern part of the town and the Dungs [N.B. another Dung] living in the southern part of the town both grow white gourds. Someone said, “The white gourds of the Dungs in the east are big.” It turns out the white gourds of the Dungs in the south are bigger than the big white gourd of the Dungs in the east.

21 圓圓 遠遠叫 圓月，叫來 圓月 來 賞月。圓圓 說：月

Yuan-yuan far call Yuan-yue called Yuan-yue to enjoy moon Yuan-yuan say moon

月圓，圓月 說：圓 圓 月。圓圓 說：圓月 的 眼 圓

full moon Yuan-yue say round round moon Yuan-yuan say Yuan-yue’s eyes round

比　月　圓。　圓月　說：　圓圓　的　圓　眼　賽　圓　月。　究竟　是

than moon round Yuan-yue say Yuan-yuan’s round eyes as round moon whether is

圓圓，　　圓月　的 眼兒　圓，還是　圓圓　　的 月兒　圓。

Yuan-yuan Yuan-yue’s eyes round　or Yuan-yuan’s moon round

Yuan-yuan called Yuan-yue from a distance to enjoy the moon. Yuan-yuan said, “The moon is round.” Yuan-yue said, “The round full moon.” Yuan-yuan said, “Your eyes are rounder than the moon.” Yuan-yue said, “Your eyes are as round as the full moon.” So, which are rounder, Yuan-yuan and Yuan-yue’s eyes or the round moon.

Captions for Figure:

Figure 1. Mean speech rate and response accuracy during pre-tDCS, post-1 and post-2 measurements.