Transcranial direct current stimulation of the motor cortex in waking resting state induces motor imagery

Speth, Jana; Speth, Clemens; Harley, Trevor A.

Published in:
Consciousness and Cognition

DOI:
10.1016/j.concog.2015.07.005

Publication date:
2015

Transcranial direct current stimulation of the motor cortex in waking resting state induces motor imagery

Jana Speth, Clemens Speth, Trevor A. Harley

School of Psychology, University of Dundee, UK

Abstract

This study investigates if anodal and cathodal transcranial direct current stimulation (tDCS) of areas above the motor cortex (C3) influences spontaneous motor imagery experienced in the waking resting state. A randomized triple-blinded design was used, combining neurophysiological techniques with tools of quantitative mentation report analysis from cognitive linguistics. The results indicate that while spontaneous motor imagery rarely occurs under sham stimulation, general and athletic motor imagery (classified as athletic disciplines), is induced by anodal tDCS. This insight may have implications beyond basic consciousness research. Motor imagery and corresponding motor cortical activation have been shown to benefit later motor performance. Electrophysiological manipulations of motor imagery could in the long run be used for rehabilitative tDCS protocols benefitting temporarily immobile clinical patients who cannot perform specific motor imagery tasks – such as dementia patients, infants with developmental and motor disorders, and coma patients.

Keywords

Brain stimulation; Motor imagery; Motor system; tDCS; Consciousness; Phenomenology; Mentation reports; Quantitative linguistic analysis; Dream; EEG

Acknowledgments

We would like to thank Sian Gilfillan, Iain Pringle, and Alex Olson for their help with the data collection and for rating the reports and evaluating the rating tools.

Introduction

Motor imagery forms an integral part of human consciousness. Such mental representations of movement without analogous body movement (Guillot & Collet, 2005) occur regularly and spontaneously, especially in states with naturally high motor cortical activation, such as rapid eye movement (REM) sleep (Desseilles et al., 2011, Dresler et al., 2011, Porte and Hobson, 1996 and Speth et al., 2013), and have been associated with motor learning and rehearsal (Hobson, 2009 and Walker et al., 2002). Motor simulation tasks can also be purposefully used in waking to benefit specific motor performances (Arora et al., 2011, Driskell et al., 1994, Jackson et al., 2006, Meister et al., 2004 and Schuster et al., 2011).

Studies revealing the strong relationship between motor simulations and motor system activation, functioning independently of motor performance (Abbruzzese et al., 1999, Bonnet et al., 1997, Decety, 1996, Fadiga et al., 1999, Jeannerod, 1995, Jeannerod, 2001, Porro et al., 1996 and Schnitzler et al., 1997) have given rise to the hope that motor imagery will provide a backdoor to the motor system after impairments (Jackson et al., 2001, Lehéricy et al., 2004 and Sharma et al., 2006). To this end, motor imagery has been shown in neurofeedback task paradigms to increase regional cortical activation: long-term effects of increased activation of motor areas involving neural circuitries associated with motor skill learning can last up to several days (Kober et al., 2014 and Yoo et al., 2008). We can assume that motor imagery and motor system activation form a functional unit that, if activated in the resting state, serves the purpose of training motor performance.

Transcranial direct current stimulation (tDCS) offers a way to manipulate cortical excitability. As it is non-invasive, has limited side effects, and is more comfortable and less irritating for participants than other brain stimulation techniques, tDCS can benefit the study of spontaneous brain activity and consciousness. Anodal tDC stimulation has been shown to increase the excitability of the motor cortex, while cathodal stimulation decreases its excitability (Nitsche & Paulus, 2000). TDCS can thus influence motor performance (Pavlova, Kuo, Nitsche, & Borg, 2014), and facilitate motor learning (Prichard, Weiller, Fritsch, & Reis, 2014). While the effects of tDCS in conjunction with motor imagery have been studied before (Foerster et al., 2013 and Quartarone et al., 2004), those studies used motor imagery as an independent variable by actively asking participants to imagine motor movements, and measured effects only on dependent physiological variables. To our knowledge, however, no study reports the direct influence of tDCS of motor areas on phenomenology, such as the experience of motor imagery.

The AIM model of consciousness proposes that the motor imagery perceived in REM sleep dreams is a direct result of higher motor cortical activation (Hobson, 2009 and Hobson et al., 2000). TDCS may also enable us to manipulate motor cortical excitability in order to test whether there is a strong causal relationship between activation of the motor system and spontaneous motor imagery as it occurs in REM sleep dreaming, or through the use of mental motor rehearsal techniques in waking.

The present study investigates if anodal and cathodal tDCS of the motor cortex elevates the degree of spontaneous motor imagery in the waking resting state. We expect anodal, but not cathodal tDCS, to induce spontaneous motor imagery compared with sham stimulation. Such tDC stimulation protocols could in the long run benefit especially such temporarily immobile clinical patients who cannot perform specific motor imagery tasks, such as mentally disabled patients, dementia patients, patients with psychological disorders, infants with developmental and motor disorders, and coma patients.

Method

To study motor imagery in the waking resting state, along with the possibility of its enhancement, mentations are investigated as conceived in a no-task-no-response setting (Vaitl et al., 2005) under anodal, cathodal, and sham stimulation. Motor imagery was measured with a quantitative linguistic tool: motor agency analysis. Agency analysis has been used in previous studies, and has been shown to be a reliable tool (Speth et al., 2015 and Speth et al., 2013). Study participants were computer randomized to the stimulation conditions. The current study is triple-blind in so far as neither the participant delivering the report, nor the investigator recording it, or the raters analysing it, knew the stimulation condition. The study was approved by the University Research Ethics Committee (UREC) of the University of Dundee, and conducted in the Dundee Sleep and Consciousness Laboratory.

Participants

Participants were male and female undergraduate volunteers. Participants were issued an information sheet on the experimental procedure, and were told that they would be asked to answer a series of questions towards the end of the testing. No further details were given on the specific purpose of the experiment in order to prevent participants from engaging in metacognitions and the planning of their verbal report or other interview responses during the mentation period. Participants were assured however that they would be able to refuse answers, without further explanation, at any time. Participants were informed about the possibility that they would feel a slight tingling sensation during the tDC stimulation. Participants with diagnoses of epilepsy or severe migraines would have been excluded from the study, along with participants who reported a history of allergic skin reactions. Written informed consent was obtained from all participants prior to the experiment.

Questionnaires

A short open-answer questionnaire assessed participants' age, gender, native language, nationality, education, medication, as well as the time of last caffeine consumption, the general level of caffeine consumption, physical exercise on the day of testing, amount of physical exercise per week, and meditation experience. Handedness was tested with a short version of the Edinburgh handedness inventory (EHI-short; Veale, 2014).

Experimental design

The experiment was conducted in a low-stimulus environment. After the investigator had attached the tDCS and EEG electrodes, participants were asked to rest in a reclining chair while a simple EEG recording of their brain would be conducted. Participants were asked to keep their eyes closed and their body movements to a minimum in order to promote the accuracy of the EEG. Participants were informed that the investigator would be in an adjacent room and return after twenty minutes. The investigator started the recording and the tDCS from the adjacent room. After twenty minutes, the investigator returned and without further ado asked participants the standardized question "What did you see, hear, feel, do in your imagination?" while offering a voice recorder. The investigator kept verbal, mimic, and gestural interaction with participants to a minimum while the report was being delivered. When participants stopped reporting, without showing the wish to continue, the investigator would stop the recording. Only after participants had finished would the investigator remove the EEG and tDCS equipment. The reports were later transcribed and handed to three blind, independent raters for the motor agency analysis.

TDCS

The tDC stimulation was carried out with a NeuroConn DC-Stimulator Plus (neuroConn GmbH, Illmenau, GER). The positioning of the tDCS rubber electrodes was the same for all three testing conditions. A smaller stimulation electrode (25 cm2) was applied at C3, while a larger (35 cm2) reference electrode was positioned contralaterally between Fp2 and F8.

A stimulation strength of 1.5 mA was applied. In order to minimize the perception of current by the participant, the current was linearly ramped up over the course of 15 s at the beginning, and ramped down over the course of 15 s at the end of the session. In order to avoid adverse effects from a sudden increase in skin resistance, the tDC stimulation would automatically stop above an impedance of 20 kΩ. In the sham condition, current was ramped up and immediately ramped down again in order to promote a perception of current onset similar to the stimulation condition.

EEG

In order to confirm that participants remained awake during the testing interval (as opposed to entering sleep stage 1), their cortical activity was monitored with a 31 channel EEG device (QuickAmp, Brain Products GmbH, Gilching, GER). An electrode cap fixated the electrodes according to the international 10–20 electrode positions. The electrode position C3 was not recorded, as it was taken up by the tDC stimulation electrode. Ag/AgCl ring electrodes were used. Participants' scalps were prepared with a 70 % isopropyl solution and an abrasive electrolyte gel (Abralyt LIGHT) in order to achieve impedance levels below 10 kΩ. In line with the AASM guidelines (Iber, Ancoli-Israel, Chesson, & Quan, 2007), EOG electrodes were placed 2 cm left and beneath the left eye, and 2 cm right and above the right eye, and two EMG electrodes were applied to the chin.

Quantitative linguistic analysis of mentation reports

The raters were asked to quantify specific linguistic references to motor imagery in the participants' mentation reports. The linguistic tool used for the rating is based on linguistic theta theory (Gruber, 2001, Reinhart, 2002 and Reinhart and Siloni, 2005). A first version of the tool has been used successfully to link degrees of linguistic references to motor imagery in mentation reports with characteristic motor cortical activation of states of consciousness (Speth et al., 2013). In a modified version, the tool has been used to investigate differences in degrees of auditory verbal hallucinations across states of consciousness (Speth et al., 2015).

The current study measures motor imagery by means of linguistic motor agency analysis. In linguistic theta system theory, the initiator of an event takes on a specific thematic (theta) role within a sentence or phrase. He or she is the agent who performs an action. In the phrase "Mimi throws a ball", Mimi is the agent. The agent is defined through his or her relationship to the predicate of a phrase: he or she is performing the action described by the predicate. Mimi is the one who is doing something. The agent is described by a noun phrase, but the agent is not necessarily congruent with the grammatical subject. Consider the following phrases, where Mimi is the agent in both (i) and (ii), but the syntactic subject only in the active version (i).

(i) Mimi opens the box.

(ii) The box is opened by Mimi.

As participants were reporting on their mental experience, it was expected that raters would encounter instances of moderated-simulated agency. Moderated-simulated agency describes how the agent engages in explicitly mental processes concerned with simulated motor action. Consider for example the phrase "I imagined myself running". In this instance, "I" is the agent of the verb phrase "imagined…", which moderates the explicitly mental, simulated activity of "running". Raters were advised to count instances of moderated-simulated agency as normal instances of simulated motor activity.

The following phrases, (iii), (iv), and (v), are samples from mentation reports. They contain instances of normal simulated motor agency as well as moderated-simulated motor agency:

(iii) And he was coming home and like holding a bunch of flowers I guess.

(iv) I imagined myself running.

(v) I think I was… I think I walking along a corridor.

Doubly or vaguely moderated action verbs however cannot be recognized as simulated agency. The following phrase (vi) for example (double moderation emphasized in bold print) would not be counted as agency, as its interpretation does not necessarily entail that the person simulated actively carrying out the tasks.

(vi) "thinking about what I needed to do"

Note that the following example (vii) does contain two motion verbs, but no agency (as there is no agent even remotely connected to the motion verbs):

(vii) Um, just like running through like a film, and stuff that I'd watched recently and stuff like that… thought of things to do on the bicycle.

Raters were instructed to count repetitions separately. The following sample (viii) contains two instances of simulated agency:

(viii) I was going along… I think I was going home with my friends.

Raters were asked to always discriminate between simulated and actual motor agency. They were instructed to count simulated agency but ignore obvious instances of actual motor agency. The following example (ix) refers to actual agency, but contains no instance of simulated motor agency:

(ix) I was moving around in this chair, just wanted to lift my head and stuff… scared that the electrodes would come off though…

Raters were instructed to count instances of agency that are described by seemingly static verb phrases such as “to be” if they can be linked to simulated agency rather than static events, as in example (x):

(x) … how I’d be in the swimming pool, you know…

Raters were asked to specify the perspective of each instance of simulated motor agency as that of the experimental subject in their imagination (first person singular, first person plural), of mentations on the temporarily absent researchers which occur in experimental settings (second person singular and plural), or as simulated motor agency of non-present real persons or imaginative characters (third person singular and plural). Ratings would thus discriminate between simulated agency experienced from a distinct first, second, or third person point of view as in example (xi), and participants’ experiences of witnessing motor imagery as though in a movie or slideshow as in example (xii):

(xi) I imagined skiing… I was skiing down a mountain.

(xii) I had this vision of rugby I think…

Raters were asked to count as normal simulated agency such instances of apparently inhibited motor agency as in example (xiii), which entail the planning, attempt, or beginning of simulated action:

(xiii) I tried to run.

As the English language comprises a vast number of movement metaphors and idioms, it needed to be ensured that those simulated motor agencies that describe distinct and intense simulations of motor movement would be captured. For example, the phrase “Mimi walked to Rome” more clearly describes physical action than “Mimi went to Rome”. Raters were thus asked to classify motor simulations as athletic disciplines where applicable (compare http://www.olympic.org/sports, https://www.theworldgames.org/the-sports/sports).

Report rating instructions

All raters were asked to rate all reports. Along with a hard copy of the reports, raters were handed an instruction manual which explained how to identify instances of simulated motor agency. The instruction manual contained the definitions of simulated motor agency that are given above. Raters were asked to use their best judgement and decide how to deal with particular phrases, as not all possible verbal references to simulated motor agency possible in natural speech can be pre-defined.

Statistical analyses

Nonparametric Kruskal–Wallis tests were conducted to ensure that the randomly assigned groups did not differ with respect to gender, native language, nationality, education, experience with meditation, time of last caffeine consumption, physical exercise prior to testing, and the amount of physical exercise per week. A one-way analysis of variance (ANOVA) was conducted to test for differences in age and laterality scores of the EHI-short between the experimental groups.

Identified instances of motor agency were aggregated for every report, separately for every rater. By calculating the mean rating of all raters for each report, one single rating value was assigned to each report. A one-way ANOVA was conducted to test for differences in the number of identified agencies between stimulation conditions and sham tDCS. Scheffé's method was used for pairwise post hoc analyses. The athletic qualities of the motor agencies were analysed in the same way.

In order to test for changes in the perspective from which motor simulations were perceived between stimulation conditions, an analysis of covariance (ANCOVA) for agency perspective (first, second, and third person) was conducted. To correct this effect for the overall changes in motor agency, the number of motor agencies was used as a covariate. Fisher's least significant difference (LSD) tests were used post hoc.

To ensure that changes in motor agency are not simply a result of changes in report length, a one-way ANOVA was conducted to test for differences in the word count of the reports from different stimulation conditions. Further, an ANCOVA tested changes in the number of motor agencies between stimulation conditions with the word count of each report as covariate. Fisher's LSD tests were used post hoc. A receiver operating characteristic (ROC) curve was calculated, and the area under the curve (AUC) was used to assert the predictive value of motor agency and athletic motor agency to determine the stimulation condition.

Results

Reports from 28 participants were collected, 7 under anodal tDCS, 8 under cathodal tDCS, and 13 under sham stimulation. The participants did not differ significantly between the experimental groups with respect to their age, gender, native language, nationality, education, medication, time of last caffeine consumption, general level of caffeine consumption, physical exercise on the day of testing, amount of physical exercise per week, experience in meditation, and their EHI-short laterality score. Analyses of the EEG data confirmed that no participants had transitioned into sleep stage 1 during the testing period.

On average the raters identified 1.43 simulated motor agencies per report (SD = 2.30). Linguistic samples from reports collected from anodal tDCS and sham can be seen in Table 1. The agreement between the three raters was high, with Cronbach's $\alpha = .98$. The prevalence of simulated motor agency differed significantly between the three stimulation conditions ($F(2, 25) = 5.93$, $p = .008$, $\eta 2 = .322$). Post-hoc analyses indicate that there were significantly more instances of simulated motor agency under anodal tDCS as compared to sham stimulation ($p = .011$). The level of athletic motor agency also differed significantly between the stimulation conditions ($F(2, 25) = 4.44$, $p = .023$, $\eta 2 = .263$). There were more athletic motor agencies (classified as athletic disciplines) under anodal tDCS than under sham stimulation ($p = .023$). Compare Figure 1.

Table 1: Report samples from anodal tDCS and sham. The type of agency (athletic, non-athletic) and the grammatical perspective (first, second, third) from which the agency is reported are given.

	sample	**Agency type and grammatical perspective**
Anodal tDCS	I imagined walking, what else did I do? I imagined running and I imagined skiing at various points...	3 x athletic first person
	It turned into a bit of Alice and Wonderland, the queen of hearts, one of the guys was painting roses red, fell over, and dropped the red paint on the ground…	3 x non-athletic third person
	I uh, I snowboarded for a bit, I kicked about, I was uhh back home for a bit walking about like […] my old neighbourhood. Uhh, I did a lot of 360's, I spun a lot in my head, I dunno…	4 x athletic first person 1 x non-athletic first person
	Uh… I dunno. I imagined myself skiing, not really much else…	1 x athletic first person
	Umm… I was fighting people as a ninja at one point…	1 x athletic first person
	I was in a room, well it had like arches and bricks, and it was all red, and I was dancing with my friends, which was quite weird…	1 x athletic first person
Sham	And in my imagination I thought… I thought a lot. About I dunno… like I was thinking about my dissertation in my head like a sad person…	N/A
	Yeah ok… things that I saw… were lots of kinda like kaleidoscope like patterns, that kinda, you know, things that I saw. […] Umm… patterns (unclear) shape birds, beaks would open and then turn to like weird rivers. I have a very weird imagination anyway, but (unclear) fairy, I did take note as I was sitting here, thinking these are really weird things that are happening, strange mickey mouse things and umm…	1 x non-athletic third person

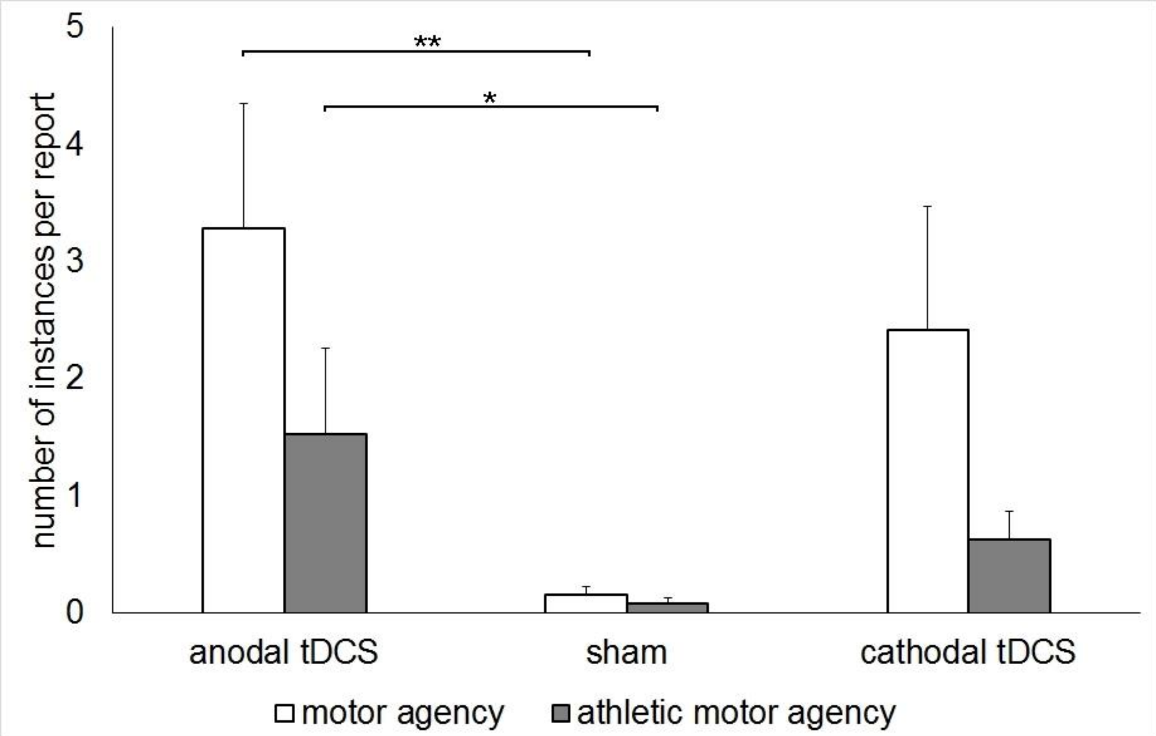

*Figure 1 Mean number of instances of motor agency and athletic motor agency per report after anodal, cathodal, or sham stimulation of C3. Error bars indicate the standard error of the mean. *p > .05, **p < .01.*

The first person perspective of agency differed significantly between the stimulation conditions ($F(2, 24) = 4.70$, $p = .019$, partial $\eta 2 = .281$). There were more instances of motor agency experienced from the first person perspective (singular and plural) in the anodal tDCS condition than in the sham condition ($p = .007$), and more in the cathodal than in the sham condition ($p = .034$). Differences for second person (singular and plural) between the stimulation conditions were not quite significant ($F(2, 24) = 3.34$, $p = .052$). The third person perspective (singular and plural) differed significantly between the stimulation conditions ($F(2, 24) = 5.45$, $p = .011$, partial $\eta 2 = .312$). There were more motor agencies for the third person (singular and plural) under sham than in the anodal condition ($p = .004$) and the cathodal condition ($p = .031$).

The number of words per report did not differ significantly between the conditions ($F(2, 25) = 2.125$; $p = .14$). The prevalence of simulated motor agency still differed significantly when correcting for the length of the report ($F(2, 24) = 4.36$, $p = .024$, partial $\eta 2 = .266$). There were more references to motor agency in reports from anodal tDCS than from sham ($p = .007$).

The ROC curve for the number of motor agencies and athletic motor agencies predicting the anodal tDCS condition can be seen in Fig. 2. For the number of motor agencies as predictor for anodal tDCS versus sham, the AUC was very large (AUC = .907) and statistically significant ($p = .003$). The AUC for the number of athletic motor agencies as predictor for the stimulation condition was not significant (AUC = .67; $p = .219$).

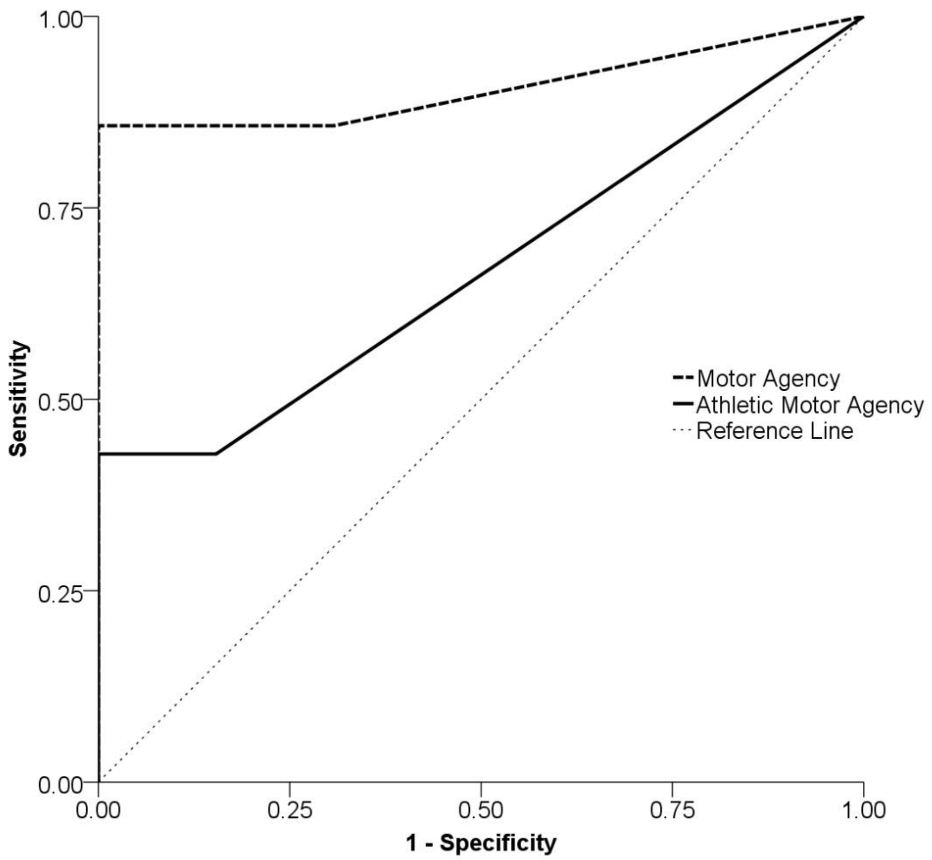

Figure 2: ROC curve for references to motor imagery and athletic motor imagery as predictor of anodal tDCS of C3.

Discussion

This study set out to investigate the effects of tDCS on human consciousness, aiming to compare the degree of motor imagery in the anodal, cathodal, and sham tDCS conditions. An implicit method (third person analysis of first person mentation reports) was used to measure motor imagery. Anodal tDCS is known to increase motor cortical excitability (Nitsche & Paulus, 2000). The present findings now indicate that anodal, but not cathodal, tDCS of areas above the motor cortex (C3) additionally increases motor imagery in general, as well as imagery of athletic motor movements (classified as athletic disciplines).

As cathodal stimulation of the motor cortex is known to decrease excitability (Nitsche & Paulus, 2000), one might expect cathodal stimulation to decrease motor imagery compared to sham stimulation. However, the present findings tentatively indicate a (non-significant) increase in motor imagery under cathodal stimulation. Future studies on the effect of cathodal stimulation on motor imagery might be able to determine whether, and how, cathodal stimulation can lead to an increase or decrease in motor imagery. It has to be considered however that under sham stimulation, a mean of 0.15 references to motor imagery was found per report. It appears difficult to decrease any further a phenomenon that almost never occurs in the first place – so that this basement effect could prevent future studies from investigating an additional decrease in motor imagery via cortical cathodal stimulation.

To account for the fact that the English language comprises a remarkably large number of manner-of-motion verbs, as well as motion and movement metaphors and idioms, raters of the mentation reports were asked to differentiate between general versus athletic motor imagery. The rationale was that this would allow for a rough distinction between weaker and stronger motor agency, while keeping the room for interpretation, as well as the cognitive load for the raters of the mentation reports, to a minimum. The tool would, for example, treat the idiom "going somewhere" as a possible linguistic artefact (as it does not necessarily denote motor imagery), but pick up "walking somewhere" (which more clearly describes athletic motor imagery). It is entirely possible that this objectivity was bought at the cost of a few cases where the tool did not pick up strong motor imagery, such as for example chopping vegetables. Both general motor imagery and athletic motor imagery could differentiate between stimulation conditions.

The present data further suggest that the increase in linguistic references to motor imagery is not an artifact of a general increase in motor speech output: The length of the report did not differ between stimulation conditions. After controlling for the word count of each report, anodal stimulation still resulted in significantly more reported motor imagery than sham stimulation. The control for word count has been criticized in the study of free mentation reports of dreams (Hobson et al., 2000), as some meaningful variables may not be independent of report length. In the present study however, it may be appropriate to control for report length, as verbal reporting involves motor action, and could have been influenced by the stimulation of motor areas. The present effect is robust to the control for word length.

The Receiver Operating Characteristic indicates that motor imagery as quantified by linguistic motor agency analysis has an excellent accuracy in differentiating between anodal tDCS and sham stimulation (AUC = .907). Motor agency is a better predictor than athletic motor agency for stimulation conditions.

It is further noted that motor imagery tended to be experienced more often from a first person, and less often from a third person point of view, in the two tDC stimulation conditions, as compared to the sham condition. These results tie in with the observation by Sirigu and Duhamel (2001) that first person motor simulations are more likely to involve motor activation than third person motor simulations.

Raters show an almost absolute agreement in quantifying motor agency in the reports. The inter-rater reliability achieved by the raters in the present study, without intense training or a psycholinguistic background, indicates that the tool of quantitative linguistic agency analysis is an easy-to-apply, reliable tool to measure simulated motor actions as they get expressed in the language of mentation reports. While the present study computer-randomized the participants to experimental groups and tested for differences in the groups that could potentially influence motor imagery (age, gender, caffeine consumption, meditation experience, physical exercise, etc.), a replication of the experiment, preferably with a within-subject design and with a larger number of participants, will strengthen the claim that brain stimulation affects motor imagery. Further research will also show if this finding extends to other states of consciousness, such as REM sleep dreaming.

So far, it can be concluded that references to motor imagery rarely occur in reports of default waking resting state mentation, and that anodal stimulation does not only moderate and increase motor imagery, but serves to generate motor imagery that would not occur spontaneously in waking resting state. The present study may be a first step towards establishing which protocol for cortical tDC stimulation induces which kinds of motor simulations – research that could be beneficial for targeted clinical applications.

References

Abbruzzese, G., Assini, A., Buccolieri, A., Marchese, R. & Trompetto, C. (1999). Changes of intracortical inhibition during motor imagery in human subjects. Neurosci. Lett., 263, 113-116.

Arora, S., Aggarwal, R., Sirimanna, P., Moran, A., Grantcharov, T., Kneebone, R., Sevdalis, N. & Darzi, A. (2011). Mental practice enhances surgical technical skills: a randomized controlled study. Ann. Surg., 253, 265-270.

Bonnet, M., Decety, L., Jeannerod, M. & Requin, J. (1997). Mental simulation of an action modulates the excitability of spinal reflex pathways in man. Cognitive Brain Res., 5, 221-228.

Decety, J. (1996). The neurophysiological basis of motor imagery. Behav. Brain Res., 77, 45-52.

Desseilles, M., Dang-Vu, T. T., Sterpenich, V. & Schwartz, S. (2011). Cognitive and emotional processes during dreaming: a neuroimaging view. Consciousness and Cognition, 20, 998-1008.

Dresler, M., Koch, S. P., Wehrle, R., Spoormaker, V. I., Holsboer, F., Sämann P. G., Obrig, H. & Czisch, M. (2011). Dreamed movement elicits activation in the sensorimotor cortex. Current Biology, 21(21), 1833-1837.

Driskell, J. E., Copper, C. & Moran, A. (1994). Does mental practice enhance performance? Journal of Applied Psychology, 79(4), 481-492.

Fadiga, L., Buccino, G., Craighero, L., Fogassi, L., Gallesse, V. & Pavesi, G. (1999). Corticospinal excitability is specifically modulated by motor imagery: a magnetic simulation study. Neuropsychologia, 37, 147-158.

Foerster, A., Rocha, S., Wiesiolek, C., Chagas, A. P., Machado, G., Silva, E., Fregni, F. & Monte-Silva, K. (2013). Site-specific effects of mental practice combined with transcranial direct current stimulation on motor learning. European Journal of Neuroscience, 37(5), 786-794.

Gruber, J. S. (2001). Thematic relations in syntax. In Baltin, M. & Collins, C., eds., The Handbook of Contemporary Syntactic Theory, 257-298. Oxford: Blackwell.

Guillot, A. & Collet, C. (2005). Contribution from neurophysiological and psychological methods to the study of motor imagery. Brain Research Reviews, 50, 387-397.

Hobson, J. A., Pace-Schott, E. F. & Stickgold, R. (2000). Dreaming and the brain: Toward a cognitive neuroscience of conscious states. Behavioral and Brain Sciences, 23, 793-842.

Hobson, J. A. (2009). REM sleep and dreaming: towards a theory of protoconsciousness. Nature Review Neuroscience, 10, 803-813.

Iber, C., Ancoli-Israel, S., Chesson, A., & Quan, S.F. (2007). The AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications. Westchester: American Academy of Sleep Medicine.

Jackson, P. L., Lafleur, M. F., Malouin, F., Richards, C. & Doyon, J. (2001). Potential role of mental practice using motor imagery in neurologic rehabilitation. Arch Phys Med Rehabil, 82, 1133-1141.

Jackson, P. L., Lafleur, M. F., Malouin, F., Richards, C. L. & Doyon, J. (2006). Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery. NeuroImage, 20, 1171-1180.

Jeannerod, M. (1995). Mental imagery in the motor cortex. Neuropsychologia, 33(11), 1419-1432.

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. NeuroImage, 14, 103-109.

Kober, S. E., Wood, G., Kurzmann, J., Friedrich, E. V. C., Stangl, M., Wippel, T., Väljamäe, A. & Neuper, C. (2014). Near-infrared spectroscopy based neurofeedback training increases specific motor imagery related cortical activation compared to sham feedback. Biological Psychology, 95, 21-30.

Lehéricy, S., Gerardin, E., Poline, J-B., Meunier, S., Van de Moortele, P-F., Bihan, D. Le. & Vidailhet, M. (2004). Motor execution and imagination networks in post-stroke dystonia. NeuroReport, 15(2), 1887-1890.

Meister, I. G., Krings, T., Foltys, H., Boroojerdi, B., Müller, M., Töpper, R. & Thron, A. (2004). Playing piano in the mind – an fMRI study on music imagery and performance in pianists. Cognitive Brain Research, 19, 219-228.

Nitsche M. A. & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. Journal of Physiology, 3, 633–639.

Pavlova, E., Kuo, M-F., Nitsche, M. A. & Borg, J. (2014). Transcranial direct current stimulation of the premotor cortex: Effects on hand dexterity. Brain Research, 1576, 52-62.

Porro, C. A., Francescato, M. P., Cettolo, V., Diamond, M. E., Baraldi, P., Zuiani, C., Bazzocchi, M. & Di Prampero, P. E. (1996). Primary motor and sensory cortex activation during motor performance and motor imagery: A functional magnetic resonance imaging study. Journal of Neuroscience, 16(23), 7688-7698.

Porte, H. S. & Hobson, J. A. (1996). Physical motion in dreams: one measure of three theories. Journal of Abnormal Psychology, 105(3), 329-335.

Prichard, G., Weiller, C., Fritsch, B. & Reis, J. (2014). Effects of different electrical brain stimulation protocols on subcomponents of motor skill learning. Brain Stimulation, 7(4), 532-540.

Quartarone, A., Morgante, F., Bagnato, S., Rizzo, V., Sant'Angelo, A., Aiello, E., Reggio, E., Battaglia, F., Messina, C. & Girlanda, P. (2004). Long lasting effects of transcranial direct current stimulation on motor imagery. Neuroreport, 15(8), 1287-1291.

Reinhart, T. (2002). The theta system. Theoretical Linguistics, 28, 229-290.

Reinhart, T. & Siloni, T. (2005). The Lexicon-Syntax Parameter: Reflexivization and Other Arity Operations. Linguistic Inquiry, 36(3), 389-436.

Schnitzler, A., Salenius, S., Salmelin, R., Jousmäki, V. & Hari, R. (1997). Involvement of primary motor cortex in motor imagery: a neuromagnetic study. NeuroImage, 6(3), 201-208.

Schuster, C., Hilfiker, R., Amft, O., Scheidhauer, A., Andrews, B., Butler, J., Kischka, U. & Ettlin, T. (2011). Best practice for motor imagery: a systematic literature review on motor imagery training elements in five different disciplines. BMC Medicine, 9(75), 1-35.

Sharma, N., Pomeroy, V. M. & Baron, J-C. (2006). Motor imagery: a backdoor to the motor system after stroke? Stroke, 37, 1941-1952.

Sirigu, A. & Duhamel, J. R. (2001). Motor and visual imagery as two complementary but neutrally dissociable mental processes. Journal of Cognitive Neuroscience, 13(7), 910-919.

Speth, J., Frenzel, C. & Voss, U. (2013). A differentiating empirical linguistic analysis of dreamer activity in reports of EEG-controlled REM-dreams and hypnagogic hallucinations. Consciousness and Cognition, 22, 1013–1021.

Speth, J., Speth, C., Harley, T. A. (2014). Auditory verbal hallucinations in waking, sleep onset, REM, and non-REM sleep. Manuscript submitted for publication.

Speth, J. & Speth, C. (2015). Memory across states of consciousness. Manuscript in preparation.

Vaitl, D., Birbaumer, N., Gruzelier, J., Jamieson, G. A., Kotchoubey, B., Kübler, A., Lehmann, D., Miltner, W. H. R., Ott, U., Putz, P., Sammer, G., Strauch, I., Strehl, U., Wackermann, J., & Weiss, T. (2005). Psychobiology of altered states of consciousness. Psychological Bulletin, 131, 98-127.

Veale, J. F. (2014). Edinburgh Handedness Inventory - Short Form: a revised version based on confirmatory factor analysis. Laterality, 19(2), 164-77.Walker, M. P., Brakefield, T., Morgan, A., Hobson, J. A. & Stickgold, R. (2002). Practice with sleep makes perfect: sleep-dependent motor skill learning. Neuron, 35(1), 205-211.

Yoo, S-S., Lee, J-H., O'Leary, H., Panych, L. P. & Jolesz, F. A. (2008). Neurofeedback fMRI-mediated learning and consolidation of regional brain activation during motor imagery. International Journal of Imaging Systems and Technology, 18(1), 69-78.

http://www.olympic.org/sports; https://www.theworldgames.org/the-sports/sports (retrieved 09/01/2014, 6:55 am)