Running title: tDCS effects on dream lucidity

Testing the involvement of the prefrontal cortex in lucid dreaming: A tDCS study

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Abstract

Recent studies suggest that lucid dreaming (awareness of dreaming while dreaming) might be associated with increased brain activity over frontal regions during rapid eye movement (REM) sleep. By applying transcranial direct current stimulation (tDCS), we aimed to manipulate the activation of the dorsolateral prefrontal cortex (DLPFC) during REM sleep to induce lucid dreaming. Nineteen participants spent three consecutive nights in a sleep laboratory. On the second and third nights they randomly received either 1 mA tDCS for 10 min or sham stimulation during each REM period starting with the second one. According to the participants' self-ratings, tDCS over the DLPFC during REM sleep increased lucidity in dreams. The effects, however, were not strong and found only in frequent lucid dreamers. While this indicates some preliminary support for the involvement of the DLPFC in lucid dreaming, further research, controlling for indirect effects of stimulation and including other brain regions, is needed.

Keywords: lucid dreaming, dorsolateral prefrontal cortex, REM sleep, transcranial direct current stimulation (tDCS)

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1. Introduction

Dreaming is often described as a state of cognitive deficiency characterized by a loss of self-reflection, bizarre, illogical situations, or a lack of control over volition and attention (Hobson, Pace-Schott, & Stickgold, 2000). On a neurophysiological level, it has been suggested that these phenomena result from hyper- or hypo- activity of specific neural networks during rapid eye movement (REM) sleep, which is the sleep stage where the most vivid dreams occur (Schwartz & Maquet, 2002). Recent neuroimaging studies have underlined that during REM sleep the brain becomes selectively deactivated as compared to waking, including the dorsolateral prefrontal cortex (DLPFC) and the precuneus, whereas other brain regions become more activated, such as the limbic and paralimbic systems (Braun et al., 1997; Maquet et al., 1996). A special kind of nocturnal dreaming is lucid where the dreamer realizes he or she is in the dream state and is often able to control dream happenings (LaBerge, 1985).

In a recent article, Hobson (2009) pointed out the relevance of lucid dreaming to the study of consciousness. Lucid dreaming has been defined as a rare but robust awareness that we are dreaming and that we are not really awake. It is considered to be mainly a REM sleep phenomenon (LaBerge, 1990), although lucidity can also occur during NREM sleep (Stumbrys & Erlacher, 2012). Hobson et al. (2000) have proposed that, during the lucid state, the previously deactivated DLPFC becomes reactivated, allowing directed thought, metacognition and awareness of being while in a dream state. Preliminary empirical evidence for this hypothesis has been obtained from a recent study (Voss, Holzmann, Tuin, & Hobson, 2009) which found that when participants become lucid, there is a shift in their EEG power, especially in the 40 Hz range and in frontal brain regions. Moreover, in lucid dreaming, EEG coherence is also largest in frontolateral and frontal areas (for all frequency bands, 1-45 Hz).

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Another recent study, which has used fMRI to study cerebral regional activation in lucid dreams, replicated these findings and showed that, in lucid dreams, not only prefrontal but also occipito-temporal cortices, bilateral precuneus, cuneus and parietal lobes exhibit higher activation compared to what occurs during non-lucid dreams (Dresler et al., 2012). Based on this background, the hypothesis was formulated that activation of the frontolateral area of the brain during REM sleep should increase the probability of lucid dreaming.

Although these findings and hypotheses concerning the neurobiology of dreams are intriguing, this research field poses several methodological challenges. One problem is the approach of activating the brain by external stimulation. In 1985, transcranial magnetic stimulation (TMS) was introduced as a neuroscience research tool able to focally and painlessly stimulate the cortex by means of a time-varying magnetic field (Barker, Jalinous, & Freeston, 1985). Although the application of TMS in sleep research is possible (Massimini et al., 2005, 2007), it is complicated due to the auditory artifacts and tactile sensations on the scalp (Noreika, Windt, Lenggenhager, & Karim, 2010). Unlike TMS, transcranial direct current stimulation (tDCS) does not induce auditory artifacts, and the voltage needed to hold the current constant decreases after a short time and usually becomes subthreshold for evoking peripheral sensations. TDCS involves continuous administration of weak currents (1 mA) through a pair of surface electrodes, cathode and anode, attached to the scalp (Nitsche & Paulus, 2000).

Several studies have demonstrated that cerebral excitability was diminished by cathodal stimulation, which is thought to hyperpolarize neurons, whereas anodal stimulation results in increased cortical excitability (Nitsche et al., 2008). These tDCS induced effects have been observed in several cortical regions such as the motor (Nitsche & Paulus, 2000), visual (Antal, Kincses, Nitsche, Bartfai, & Paulus, 2004), somatosensory (Rogalewski, Breitenstein, Nitsche, Paulus, & Knecht, 2004) and the prefrontal cortex (Karim et al., 2010). In 2004, it was demonstrated for the first time that tDCS can be reliably applied during sleep

without awakening the participants (Marshall, Mölle, Hallschmid, & Born, 2004). Moreover, it was found that repeated application of anodal tDCS over frontocortical areas during slow wave sleep (SWS) improved declarative memory consolidation. Furthermore, another group of researchers recently explored the effects of simultaneous tDCS stimulation on the frontal and posterior parietal cortices during different stages of sleep (Jakobson, Conduit, & Fitzgerald, 2012; Jakobson, Fitzgerald, & Conduit, 2012a, 2012b). While cathodal-frontal and anodal-parietal stimulation increased reported visual dream imagery during Stage 2 sleep (Jakobson, Fitzgerald, et al., 2012b), no such effects were observed during slow wave sleep (Jakobson, Fitzgerald, et al., 2012a) and the reversed stimulation (i.e. cathodal-parietal, anodal-frontal) did not have an effect on visual imagery during REM sleep (Jakobson, Conduit, et al., 2012).

In order to go beyond the correlational data regarding the neural correlates of dream lucidity as suggested by previous EEG and fMRI studies (Dresler et al., 2012; Voss et al., 2009), we aimed in this study to experimentally manipulate the activation of the prefrontal brain cortex and test the neurobiological basis of dream lucidity. Anodal tDCS was applied during REM sleep to activate the DLPFC and – by modulating cortical excitability – should have had an effect on subjective experience of dreaming by increasing the probability of lucid dreaming.

2. Material and methods

2.1. Participants

Twenty-three participants (7 male, 16 female) aged from 21 to 33 years (M = 25.0 ± 3.1) were recruited for the study via e-mail advertisements sent out to psychology students and known lucid dreamers. The inclusion criteria were: (1) at least average dream recall (one or more recalled dreams a week); (2) good sleeping; (3) no serious health problems, chronic illnesses

and/or medication intake. An additional criterion, which was employed towards the middle of the study, was a higher frequency of lucid dreaming: During recruitment participants were asked to estimate their lucid dreaming frequency on a 7-point scale (see 2.5 below) and those with a higher frequency of lucid dreams (e.g. once a month or higher) were invited to participate in the study. The exclusion criteria were: (1) presence of sleep disorders (sleep apnea and periodic limb movements during sleep), and (2) high sensitivity to tDCS (some participants awakened every time the simulation was applied during REM sleep). This was tested during the first (adaptation) night. Three participants were withdrawn from the study due to high tDCS sensitivity after the first night. Furthermore, one participant withdrew after the second night due to not being able to sleep in the sleep laboratory. Therefore, only 19 participants completed the study (6 male / 13 female; age range: 21 – 33, M = 25.1 ± 3.2). All participants signed an informed consent form and were paid for their participation. Ethical approval for the study was obtained by the Ethics Committee of the Medical Faculty Mannheim / Heidelberg University.

2.2. Procedure

The participants spent three consecutive nights in the sleep laboratory with continuous polysomnographic recording (from about 23:00 to about 7:00). Before the first night, the participants were asked to complete a questionnaire about their dream and lucid dream frequency (see section 2.5 below). The first night served as an adaption night, during which the participants were also screened for sleep disorders (sleep apnea and periodic limb movements during sleep) and for sensitivity to tDCS: Several times during the night, tDCS was shortly applied during REM sleep. If after each application the participant was awakened, he or she was considered as being too sensitive to tDCS and was withdrawn from further participation in the study. Before going to sleep, the stimulation was demonstrated to the participants (1 mA for 3 min), so they could see if they are comfortable with the sensations.

The second and third nights served as experimental nights. In a randomized and counter-balanced order, the participants received tDCS stimulation one night while, during the other night, they received sham stimulation. The participants were blind as to which condition on which night they received. Prior to bedtime, the participants were instructed to produce a specific sequence of eye movements (left-right-left-right-left-right, LRLRLR) when they realized they were dreaming (LaBerge, Nagel, Dement, & Zarcone, 1981) and to repeat the signal at a rate of about once a minute while still retaining lucidity. Furthermore, they were instructed on awakening to describe their dream as detailed as they could and report on all their cognitive activities, sensory qualities, locations, events, actions, people and objects.

The stimulation was delivered in each REM period, starting with the second REM period of the night. One minute after the stimulation was ended, the participants were awakened via an intercom system by calling their name and were asked to report any mental content that was in their mind before the awakening. Further, they were asked to confirm whether they gave any LRLRLR signals and several additional questions about their experience during the dream (see section 2.5 below). Moreover, they were asked if this dream was somehow different (unusual) in comparison to their other sleep laboratory dreams or dreams at home. The dream reports were recorded by a portable voice recorder, transcribed, randomly permutated and rated by a "blind" judge (see section 2.6 below).

2.3. Polysomnography

For the first night, polysomnography included electroencephalogram (EEG: F3-A2, F4-A1, C3-A2, C4-A1, CZ-A1, O2-A1, O1-A2), electroocculogram (EOG), submental and leg (left and right anterior tibial muscles) electromyogram (EMG), electrocardiogram (ECG) and respiration (oral and nasal airflow, thoracoabdominal respiratory movements, and oxygen saturation). For the second and third nights, polysomnographic recording encompassed EEG (FZ-A1, C3-A2, C4-A1, O2-A1, O1-A2), EOG, submental EMG and ECG. EEG electrodes

were placed according to the international Ten-Twenty system (Jasper H H, 1958). Sleep stages were manually scored according to the AASM criteria (Iber, Ancoli-Israel, Chesson, & Quan, 2007).

2.4. TDCS stimulation

For tDCS stimulation, two battery-driven devices DC-Stimulator CX-6650, Model TRCU-04A were used, manufactured by Rolf Schneider Electronics (Goettinger Landstr. 10, D-37130 Gleichen). The stimulation was delivered through two pairs of conductive rubber electrodes (4 cm x 3 cm) that were put inside saline soaked sponges (6 cm x 5 cm). Synapse conductive electrode cream was applied between the internal side of the sponge and the rubber electrode, and on the external side of the sponge which was attached to the skin. Each anode was applied to the DLPFC (positions F3 and F4 according to the Ten-Twenty-system, as used in other tDCS studies, e.g. Fecteau et al., 2007; Fregni et al., 2005), whereas the cathodes were applied to the supraclavicular area of the same side. The anodes were fixed on the scalp by using a tubular net bandage, while the cathodes were fixed using an adhesive tape.

During the tDCS stimulation nights, the direct current of 1 mA was delivered for 10 minutes with a fade-in period of 10 s and a fade-out period of the same length. If, during the stimulation the participant awakened or entered Stage 2, the stimulation was discontinued and resumed only if the same REM period continued (a 15 min criterion was used to define separate REM periods). During the sham stimulation nights, only a fade-in period of 10 s (ramping to 1 mA) of tDCS was delivered to mimic possible physical sensations, such as tingling, on the skin (Gandiga, Hummel, & Cohen, 2006).

2.5. Self-questionnaires

Prior to the first night, participants were asked to indicate their dream and lucid dream recall frequency during the previous few months. Dream recall frequency was measured on a 7-point scale (0 - never, 1 - less than once a month, 2 - about once a month, 3 - twice or three times a month, 4 - about once a week, 5 - several times a week, 6 - almost every morning). This scale has been shown to have a high retest reliability (r = .85; Schredl, 2004). The frequency of lucid dreams was measured on a 8-point scale (0 - never, 1 - less than once a year, 2 - about once a year, 3 - about 2 to 4 times a year, 4 - about once a month, 5 - about 2 to 3 times a month, 6 - about once a week, 7 - several times a week; Schredl & Erlacher, 2004).

Upon each REM awakening, after a dream report, the participants were asked to evaluate the intensity of positive and negative emotions during their dreams on two 4-point scales (0 – none, 1 – mild, 2 – moderate, 3 – strong) and answer two questionnaires verbally: Metacognitive, Affective, Cognitive Experience questionnaire (MACE, Kahan & LaBerge, 2011) and Dream Lucidity Questionnaire (DLQ).

MACE contains 7 items, scored on a 5-point scale (anchor points: 0 – none, 2 – some, 4 – all) that assess different types of metacognitive activities: choice, suddenly captured attention, focused attention, public self-consciousness and reflective awareness of own thoughts/feelings, own behavior and external events.

DLQ was an especially devised questionnaire to measure different aspects of lucidity within dreams. It consists of 12 items, scored on a 5-point scale (0 – not at all, 1 – just a little, 2 – moderately, 3 – pretty much, 4 – very much) that evaluate different types of awareness (awareness of dreaming, awareness that physical body is asleep, awareness that dream characters and objects are not real, awareness of different possibilities), control (deliberately choosing an action, changing dream events, dream characters, dream scene, breaking the physical laws), and remembrance (of waking life and of intentions) (see section 3.1 below for the questionnaire items).

To reduce the number of variables and statistical tests required, factor analysis was carried out for both the MACE and DLQ questionnaires for the whole set of collected dream report ratings.

2.6. Judge ratings

After dream reports were transcribed and permutated, they were scored by an external judge (who was unaware of which participant and which condition the dream report belongs) for lucidity and bizarreness. Dream lucidity was evaluated on a 3-point scale (0 – no evidence of a lucid dream, 1 – possible indications of a lucid dream, 2 – clear indication of a lucid dream). For the assessment of dream bizarreness, a 4-point scale was used (1 – possible in waking life and also occurs in normal, everyday life; 2 – many elements of waking life, but with unusual sequences and connections, yet realistic; 3 – one or two fantasy objects, bizarre connections or actions impossible in waking life; 4 – frequent/numerous fantasy objects, bizarre connections or actions impossible in waking life). The number of bizarre elements within the dreams was also calculated.

Both bizarreness measures had been used in previous research and showed good interrater reliability: bizarreness scale r=.69-.78 (Schredl, Burchert, & Gabatin, 2004); a number of bizarre elements within the dream r=.91 (Schredl & Erlacher, 2003). To evaluate interrater reliability of the lucidity scale, a second external judge was used (who scored dream reports for lucidity only).

2.7. Statistical analysis

IBM SPSS Statistics 17 software was used for the statistical analysis. Statistical tests were applied with alpha = .05. Non-parametric Wilcoxon signed-rank test was used for comparing the two conditions. 1-tailed statistical tests were applied within the direction of our hypothesis

(i.e., that tDCS will increase lucidity in dreams) while 2-tailed tests were applied in those cases where no predictions were made.

3. Results

For nineteen participants, who completed the study, the median value for reported dream recall frequency was "several times a week" and the median value for reported lucid dream frequency was "about once a month". Eleven participants could be considered frequent lucid dreamers according to the terminology of Snyder and Gackenbach (1988) (lucid dreaming frequency is once a month or higher).

A total of 110 REM awakenings were made (in average, 5.8 per participant). The comparative data on awakenings between the two conditions is provided in Table 1. Stimulation had disruptive effects on REM sleep - in many cases participants awakened when tDCS was applied. There were thus fewer awakenings in the tDCS condition and awakenings were made later considering both average time since sleep onset and (to some extent) average clock time in comparison with sham stimulation nights. For three participants, who were very sensitive to the stimulation, no awakenings were possible during the tDCS night. No differences were found in the dream recall rates and unusual dream report rates.

A lucid dream was recorded with LRLRLR eye signaling only once during REM sleep (tDCS night). The participant signaled twice (after 3 and 4 min since the beginning of stimulation) and awakened by herself after the second eye-signaling. Eye-signaling occurred during the third REM period, 4 hours 21-22 min after sleep onset. Notably, earlier in the same night, the participant also signaled from NREM sleep (N2), which has been described elsewhere (Case 1; Stumbrys & Erlacher, 2012).

Six times one of the tDCS cables became disconnected and only one side of DLPFC was stimulated. Three times on those occasions no dream had been recalled and the remaining three dream reports were excluded from comparative dream analysis.

Insert Table 1 about here

3.1. Factor analysis

A two-factor structure emerged for the MACE questionnaire, explaining 54.6% of variance (Table 2). The first factor (F1) could be described as "metacognition with internal focus" and the second (F2) as "metacognition with external focus". Overall rating scores (averages) for both components were calculated.

Insert Table 2 about here

For the DLQ questionnaire, a first main factor emerged, explaining 44.1% of variance (Eigenvalue=5.286), while Eigenvalues of other factors were below 1.5. This suggests that there is an underlying construct of "lucidity" (Table 3). For calculating the overall lucidity rating score, two items (No. 7 and 12) that loaded poorly (<.4) were excluded. Notably, those two items dealt with recall of waking facts, episodes or intentions. The overall DLQ lucidity score correlated positively with the MACE "metacognition with external focus" subscale (r=.212, p=.018, 1-tailed), but not with the MACE "metacognition with internal focus" subscale (r=.086, p=.200, 1-tailed).

Insert Table 3 about here

3.2. Self- and judge ratings

A comparison of dream report data for two conditions is provided in Table 4. As no REM awakenings for tDCS nights were possible for three participants, the sample was reduced to 16 participants. Emotional tone was calculated as the difference between positive and negative feelings (range from -3 to 3). Interrater agreement for the lucidity rating was r=.86 and lucid dreams were identified correspondingly.

On tDCS nights, dream reports were significantly longer than on sham stimulation nights. Furthermore, the participants rated their dreams from tDCS nights to be more lucid than their dreams from sham nights. No differences were found in self-reported emotional tone of the dreams or metacognitive activities within the dreams. Self-reported lucidity was not associated with dream report length (r=-.029, p=.776), awakening clock time (r=.078, p=.447) or time since sleep onset (r=.104, p=.308). Self-reported metacognition was also not associated with the awakening time; however, longer dream reports had more externally-focused metacognition (r=.228, p=.024). Metacognition with internal focus was not associated with dream report length (r=.160, p=.116).

The judge scored seven dream reports as with clear indications of lucidity: 4 out of 40 (10%) from tDCS nights and 3 out of 55 (5.5%) from sham nights. According to the judge ratings, dreams from tDCS nights were more lucid and somewhat more bizarre (less realistic but without differences in numbers of bizarre elements). An initial analysis of the judge ratings showed that external lucidity and bizarreness ratings were associated with the dream length (correlations with dream report word count: lucidity r=.206, bizarreness r=.344, number of bizarre elements r=.255, all p<.05). To control this variable, we computed regression analyses and then compared the residuals. When controlled for the dream length, there were no differences in dream lucidity and bizarreness between the two conditions (only a non-significant trend for higher bizarreness in dreams from tDCS nights; Table 4).

Insert Table 4 about here

3.3. Post-hoc analyses

Post-hoc DLQ sub-item analysis showed that on tDCS nights, the participants were more aware that dream objects were not real (0.719 ± 1.341 vs. 0.292 ± 0.769, Z=-1.753, p=.040). There were also tendencies for them to be more aware that their dream characters were not real people (0.797 ± 1.418 vs. 0.365 ± 0.830, Z=-1.332, p=.092) and their physical body was asleep (0.625 ± 1.218 vs. 0.369 ± 0.889, Z=-1.439, p=.075), as well as making more deliberate choices (0.823 ± 0.963 vs. 0.769 ± 1.191, Z=-1.471, p=.071) during tDCS nights.

Another post-hoc analysis was made by separating participants into two subgroups: (1) frequent lucid dreamers (frequency of lucid dreaming is once a month or higher) and (2) infrequent or non-lucid dreamers. Each subgroup consisted of eight participants. The subgroup analysis revealed that only frequent lucid dreamers had increased dream lucidity on tDCS nights in comparison to sham nights (0.917 ± 0.881 vs. 0.599 ± 0.626, Z=-2.117, p=.017) while no difference was found for infrequent and non-lucid dreamers (0.058 ± 0.068 vs. 0.087 ± 0.101, Z=-0.171, p=.568). The aforementioned differences on a DLQ single item level in greater awareness about unreality of dream objects and dream characters, as well as about the sleeping physical body were all statistically significant for frequent lucid dreamers (p<.05), but not for infrequent and non-lucid dreamers. However, infrequent and non-lucid dreamers made more deliberate choices during tDCS nights (p<.05).

Furthermore, we checked if lucidity might be explained by increased arousal to tDCS. An additional micro-arousal analysis has been conducted for those tDCS and sham stimulation episodes from which dream reports were collected (one or two epochs at the beginning and at the end of the stimulation have been excluded as EEG signals were

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uninterpretable due to tDCS effects). Micro-arousal episodes were counted according to the criteria of the American Sleep Disorders Association (Bonnet et al., 1992). The number of micro-arousals per REM period was not different between tDCS and sham conditions (1.11 ± 0.85 vs. 0.96 ± 0.72; Z=-0.369; p=.712) and there was no association between the number of arousals and the reported dream lucidity rating (r=.058, p=.573).

4. Discussion

TDCS stimulation delivered over the DLPFC during REM sleep had an effect on the subjective experiences of dreaming. As hypothesized, it resulted in increased dream lucidity according to the self-rating of participants. This study thus provides preliminary empirical support for the causal involvement of the DLPFC in lucid dreaming. The effects, however, were not very strong and post-hoc analysis showed that they were pronounced only in frequent lucid dreamers, who reported increased awareness that their physical body is asleep, that dream objects and dream characters are not real, as well as overall lucidity. No effects of increased lucidity were reported by infrequent and non-lucid dreamers. External "blind" judge scored dream reports from tDCS nights as more lucid and somewhat more bizarre than dream reports from sham nights, yet when judge ratings were controlled for dream report length, the differences in lucidity were no longer significant and differences in bizarreness remained only marginal. One possible explanation is that in shorter dream reports it might be difficult for an external judge to recognize explicit signs of dream lucidity.

It is possible that activation of a wider network of different brain areas is needed to achieve steady lucidity in dreams. For example, Dresler et al. (2012) found an increased activation during REM lucid dreams, not only in the prefrontal, but also in the occipito-temporal cortices, bilateral precuneus, cuneus and parietal lobes. These cerebral areas can also be targeted for stimulating lucid dreaming. On another hand, a combined tDCS and PET of regional cerebral blood flow (rCBF) study found that both cathodal and anodal tDCS induced

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increases and decreases in rCBF, not only in the cortical areas beneath the electrodes, but also in a much wider network of cortical and subcortical areas (Lang et al., 2005). Thus it is possible that not only the DLPFC but also some other brain regions have also been activated due to the stimulation.

Further, there is a possibility that lucidity occurred due to indirect effects of tDCS application. For example, the stimulation might have increased arousal which could lead to increased lucidity, as lucid dreams are associated with elevated levels of physiological activation during REM sleep (LaBerge, Levitan, & Dement, 1986), or lucidity might be induced due to electro-tactile stimulation effects (cf. Hearne, 1983). To explore such possibility we carried out an additional analysis of micro-arousals for those REM periods from which dream reports were collected. While we did not found more arousals during tDCS as compared to the sham condition and there was not association between the number of arousals and reported dream lucidity, we can not completely rule out such a possibility. To control for this, futures studies, in addition to the sham condition, are advised to use stimulation over another brain region or to compare anodal vs. cathodal stimulation..

Furthermore, it might be that the activation itself has not reached a sufficient threshold to induce lucidity. For example, a combined tDCS and blood oxygenation level dependent (BOLD) MRI study found that while cathodal tDCS resulted in a significant global decrease of activated pixels by 38%, anodal tDCS yielded only a 5% (insignificant) increase (Baudewig, Nitsche, Paulus, & Frahm, 2001). More pronounced effects found in frequent lucid dreamers might suggest that due to their frequent experience, the required DLPFC activation threshold might be somewhat lower or their DLPFC is already more activated during REM sleep as compared to what would be needed with infrequent and non-lucid dreamers (a hypothesis to be tested in future studies).

In many cases tDCS applied during REM sleep was somewhat disturbing for the participants – it disrupted REM sleep and resulted in brief awakenings. Thus the number of

awakenings was lower on tDCS nights (for three participants no awakenings were possible at all) and awakenings were carried out later. This also explains longer dream reports for the tDCS nights: If the stimulation awakened a participant, it was discontinued and reapplied if the participant re-entered REM sleep; the participants could therefore spend more time in REM sleep during the tDCS nights. This, however, did not affect lucidity ratings – lucidity was neither associated with awakening times nor with dream report lengths.

Another study which applied tDCS during REM also reported cases where the stimulation disrupted REM sleep each time it was applied (Jakobson, Conduit, et al., 2012). In our study, the participants often started to scratch the area of stimulation upon the application of tDCS, indicating some itching sensations. To eliminate those sensations, in future studies topically applied local anesthetic cream, such as EMLA, could be used (McFadden, Borckardt, George, & Beam, 2011).

In the present study only one lucid dream was verified with volitional eye-movements, despite the fact that lucidity was observed in much more dreams (seven dreams, for example, were scored as clearly lucid by an external judge). In many cases the participants forgot to signal after becoming lucid in a dream. Our recent survey, which included 571 lucid dreamers, revealed that waking memory recall is often impaired in lucid dreams - in average lucid dreamers are able to recall only a half those actions that they plan in wakefulness for accomplishment in lucid dreams (Stumbrys, Erlacher, Johnson, & Schredl, 2013). In the present study these numbers were markedly lower. One possible reason is that our participants were only briefly instructed about LRLRLR eye-signaling before going to sleep and a more extensive training and mental set preparation is needed to ensure a better recall. Awakening after a longer time in REM sleep might also increase the chances for successful eye-signaling (cf. LaBerge et al., 1986).

The finding that infrequent and non-lucid dreamers were making more deliberate choices in their dreams on tDCS nights can be explained by involvement of the DLPFC in

decision making, especially in ambiguous situations (Krain, Wilson, Arbuckle, Castellanos, & Milham, 2006). On another hand, dreams of frequent lucid dreamers on tDCS nights were marked by an increased awareness that their physical body was asleep and that their dream characters and dream objects were not real. DLPFC is known to play an crucial role in working memory (Curtis & D'Esposito, 2003), which is necessary for recognizing and maintaining the awareness of the dream state and its illusory nature. Furthermore, it has been demonstrated that of all brain regions, the DLPFC is exclusively associated with conscious perception (Lau & Passingham, 2006), which is, of course, the cornerstone of lucidity in dreams.

In this study it was also found that lucidity in dreams had some associations with externally-focused metacognition but not with internally-focused metacognition. Lucid dreams are often initiated by observing an oddity within the dream environment (Purcell, Mullington, Moffitt, Hoffmann, & Pigeau, 1986); metacognitive activities with external focus might therefore play a more important role in lucid dreaming.

TDCS did not affect the emotional tone of dreams and dreams from stimulation nights were not reported to be more unusual than dreams from sham nights, yet the external judge scored them to be somewhat more bizarre. While it has been suggested that prefrontal deactivation accounts for bizarreness in dreams (Muzur, Pace-Schott, & Hobson, 2002), lucid dreams, on the other hand, are associated with higher dream bizarreness (McCarley & Hoffman, 1981). The relation between dream lucidity and bizarreness could be two-fold. On one hand, bizarreness might help to facilitate lucidity (e.g. by recognizing an oddity), while on the other hand in lucid dreams the dreamer can do bizarre things that are impossible in waking life, such as flying (Barrett, 1991). Future studies should explore the involvement of the prefrontal cortex in dream bizarreness by applying cathodal (inhibitory) stimulation during non-lucid dreaming.

When interpreting the results, some methodological considerations have to be acknowledged. Different placements of the second tDCS electrode might yield qualitatively different effects (Nitsche et al., 2008). For example, the tDCS sleep study by Marshall et al (2004) applied the cathode electrodes at the mastoids while, in this study, the cathodes were applied at the supraclavicular areas. Furthermore, carry-over effects of tDCS to subsequent REM periods might also occur (Nitsche et al., 2008); yet, in this study, lucidity was not associated with later awakening times. Also the present study was conducted as a single-blind experiment and, despite all precautions taken, some possibility of the experimenter's bias remains (e.g. by unintentionally giving cues which night was which or by a voice tone when reading lucidity questions aloud).

In summary, this study provides some preliminary evidence for involvement of the DLPFC in lucid dreaming. While this causal connection is important on the neurophysiological level, due to the small effects, tDCS might not be a promising tool for lucid dream induction on a practical level (Noreika et al., 2010). For practical purposes, other lucid dream induction methods can be suggested (Stumbrys, Erlacher, Schädlich, & Schredl, 2012). Future studies could target other brain areas, such as the precuneus, to increase the probability of lucid dreaming, as well as higher stimulation intensities (e.g. 2 mA) with topically applied local anesthetic creams. To control for indirect tDCS effects, in addition to sham stimulation, the stimulation over another brain region or inversed stimulation (anodal vs. cathodal) should also be used. To increase the frequency of lucid dreams with volitional eye-signaling, more extensive mental set preparation training should be employed and awakenings carried out after a longer time in REM sleep.

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Table 1. Data on awakenings (N=19 participants)

	Sham			tDCS			Z	p-val
	M	SD	Range	M	SD	Range		(2-tailed)
Number of awakenings	3.21	1.03	2 - 5	2.53	1.81	0 - 7	-1.960	.050*
Dream recall rate (%)[1]	90.4	15.7	50 - 100	90.4	15.9	50 - 100	-0.254	.799
Unusual dream report rate (%)[1]	19.7	30.1	0 - 100	25.9	35.4	0 - 100	-0.772	.440
Average awakening clock time[1]	5:07	0:44	4:05 - 6:23	5:40	1:09	3:48 - 7:44	-1.862	.063[+]
Average awakening time since sleep onset[1]	5:55	0:46	4:58 - 7:18	6:29	0:58	4:46 - 8:15	-2.379	.017*

Note: [1]N=16 for tDCS condition; *$p \leq .05$, [+]$p < .1$

Table 2. Factor loadings for MACE questionnaire items

Item	F1	F2
Making choice	**.711**	-.072
Attention captured suddenly	-.121	**.787**
Focused attention	**.500**	.311
Public self-consciousness	**.780**	-.020
Awareness of own thoughts/feelings	**.704**	-.119
Awareness of own behavior	**.594**	.377
Awareness of external events	.096	**.775**

Note: Oblimin rotation with Kaiser normalization.

Table 3. Factor loadings (unrotated) for DLQ questionnaire items

Item	
1. I was aware that I was dreaming	**.869**
2. I was aware that my physical body was asleep	**.843**
3. I was aware that all my dream characters were not real people	**.872**
4. I deliberately chose one action instead of the other	**.417**
5. I was aware that all dream objects were not real	**.920**
6. I changed dream events in the way I wanted	**.728**
7. I recalled some facts or episodes from my waking life	.314
8. I changed dream characters in the way I wanted	**.574**
9. I broke the physical laws of the waking reality (e.g., flew, went through a wall)	**.577**
10. I changed the dream scene in the way I wanted	**.629**
11. I thought about different possibilities of what can I do in a dream	**.550**
12. I clearly remembered my intentions of what I wanted to do in a lucid dream	.225

Table 4. Comparison data on dream reports for two conditions (N=16 participants)

	Sham		tDCS		Z	p-value
	M	SD	M	SD		
Word count	116.6	70.7	159.9	111.1	-2.430	.015*[a]
Self-ratings						
Emotional tone	0.510	0.741	0.318	1.114	-0.544	.586[a]
Lucidity (DLQ)	0.343	0.507	0.488	0.749	-1.798	.036*[b]
Metacognition with internal focus (MACE)	1.123	0.803	1.187	0.860	-0.854	.197[b]
Metacognition with external focus (MACE)	1.202	0.937	1.330	0.914	-0.028	.489[b]
Judge ratings						
Lucidity	0.167	0.365	0.396	0.611	-2.070	.019*[b]
Bizarreness	1.660	0.513	1.929	0.523	-2.282	.022*[a]
Number of bizarre elements	0.219	0.415	0.242	0.393	-0.315	.752[a]
Judge ratings (controlled for dream report length[1])						
Lucidity	-0.060	0.362	0.121	0.571	-0.724	.235[b]
Bizarreness	-0.163	0.471	-0.002	0.494	-1.810	.070[+a]
Number of bizarre elements	-0.032	0.400	-0.076	0.382	-0.621	.535[a]

Note: *p<.05, [+]p<.1; [a]2-tailed test, [b]1-tailed test; [1]residuals are provided.