Testing the prefrontal hypothesis of lucid dreaming: A tDCS study

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Abstract

REM sleep is marked by decreased activity of the prefrontal cortex areas, which has been associated with the bizarreness of dreams and the absence of self-reflective consciousness of the dreamer. The loss of self-reflection is recovered in so called lucid dreams in which the dreamer is aware that he or she is dreaming. Recent studies suggest that lucid dreaming is associated with increased activity over frontal regions during REM sleep. We tested this prefrontal hypothesis of lucid dreaming by applying transcranial direct current stimulation (tDCS) over the DLPFC during REM sleep. Twenty-three participants were recruited for a randomized blinded study and 19 of them completed the study by spending three consecutive nights in a sleep laboratory with polysomnographic recording. The first night served as an adaptation night, while 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). Then participants were awakened and asked for a dream report and self-ratings of metacognitive activities and lucidity within the dream. The dream reports were also scored by a "blind" judge. According to both the self-ratings and the external rating of the judge, tDCS stimulation over the DLPFC during REM sleep increased lucidity in dreams. Therefore our results provide direct empirical support for the involvement of the DLPFC in lucid dreaming. The effects, however, were not very strong and pronounced only in frequent lucid dreamers, suggesting that practical applications of tDCS for lucid dream induction might be limited.

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

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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 hypoactivity of specific neural networks during rapid eye movement (REM) sleep, which is the sleep stage in which the most vivid dreams occur (for a review see Schwartz & Maquet, 2002). Recent neuroimaging studies have underlined that the sleeping brain becomes selectively deactivated compared to waking such as the dorsolateral prefrontal cortex (DLPFC) and the precuneus, whereas other brain regions become more activated such as the limbic and paralimbic systems (Dang-Vu et al., 2007). A special kind of nocturnal dreams is lucid dreaming. In a lucid dream the dreamer realizes the dream state and he or she is often able to control the dream simulation and do whatever he or she wants to do (Schredl & Erlacher, 2004).

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. Lucid dreamers even often claim, that they can gain control over the course of the dream. Kahn and Hobson (2005) have proposed that during the lucid state the previously deactivated DLPFC becomes reactivated. This reactivation would allow directed thought, metacognition and awareness of being in a dream. Preliminary empirical evidence for this hypothesis has been obtained from a recent study by Voss, Holzmann, Tuin and Hobson (2009) in which three student volunteers had been trained by pre-sleep autosuggestion to become lucid. Their findings indicate that when subjects become lucid, there is a shift in their EEG power, especially in the 40-Hz range and especially in frontal brain regions. Moreover, in lucid dreaming also EEG coherence is largest in frontolateral and frontal areas. Another recent study, which has used fMRI to study brain regional activation in lucid dreams, replicated findings by Voss et al. (2009) and showed that in lucid dreams not only prefrontal but also occipito-temporal cortices, bilateral precuneus, cuneus and parietal lobules show higher activation compared to 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 result increase the probability of lucid dreaming. Although these findings and hypotheses concerning the neurobiology of dreams are intriguing, this fascinating research field poses several methodological challenges. One problem is the methodological approach of activating the brain by external stimulation. Barker, Jalinous and Freeston (1985) introduced transcranial magnetic stimulation (TMS) as a neuroscience research tool able to focally and painlessly stimulate the cortex by creating a time-varying magnetic field. However, TMS application in sleep research 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 artefacts, 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 hyperpolarizes neurons, whereas anodal stimulation resulted in increased cortical excitability (for a review see 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, Marshall, Mölle, Hallschmid and Born for the first time demonstrated that tDCS can be reliably applied during sleep without awakening the subjects. Moreover, they 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. While cathodal-frontal and anodal-parietal stimulation increased reported visual dream imagery during Stage 2 sleep (Jakobson, Fitzgerald, & Conduit, 2012a), no such effects were observed during slow wave sleep (Jakobson, Fitzgerald, & Conduit, 2012b) and the reversed stimulation (i.e. cathodal-parietal, anodal-frontal) did not have effect on visual imagery during REM sleep (Jakobson, Conduit, & Fitzgerald, 2012).

In order to go beyond the correlational data regarding the neural correlates of dreaming, we apply tDCS in this study for probing the neurobiological basis of specific dream characteristics. Anodal tDCS could be applied during REM-sleep to activate the DLPFC and should – by stimulating cortical excitability – increase the probability of lucid dreaming.

Methods

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) high dream recall (at least once a week); (2) good sleeping; (3) no serious health problems, chronic illnesses and medication intake. An additional criterion was a higher frequency of lucid dreaming – towards the middle of the study during the recruitment the participants were asked to estimate their lucid dreaming frequency on a 7-point scale (see below) and we invited those with a higher frequency of lucid dreams to participate in the study. The exclusion criteria were: (1) presence of sleep disorders (sleep apnea or restless legs syndrome), (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 and University Medical Centre Mannheim at Heidelberg University.

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 also completed questionnaires about their sleep, dreams and metacognition (see below). The first night served as an adaption night, during which the participants were also screened for sleep disorders (sleep apnea and restless legs syndrome) 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 too sensitive to tDCS and was withdrawn from the 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 night served as experimental nights. In a randomised and counter-balanced order, one night the participants received tDCS stimulation, while during the other night they received sham stimulation. The participants were blinded to which condition 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 will realize that are dreaming (cf. LaBerge, Nagel, Dement, & Zarcone, 1981) and repeat the signal at a rate about once a minute while they still retain lucidity. They were also provided with two reality testing techniques, using which they could be able to test if they are dreaming or not: (1) close their mouth and nose and try to breath; (2) jump into the air and observe the gravity when landing. Furthermore, they were instructed on awakening to describe their dream as detailed as they can and report all their cognitive activities (thinking, planning, imagining, evaluating, remembering, feeling, talking, listening, attending to outside world, attending to inner world), sensory qualities (smell, touch, taste, sounds, colours, brightness, movement), locations, events, actions, people and objects.

The stimulation was delivered in each REM period starting from the second REM period of the night. One minute after the end of the stimulation, the participants were awakened via intercom system by calling their name and asked to report any mental content that was in their heads before the awakening. Further, they were asked to confirm whether they gave any LRLRLR signal and several additional questions about their experience during the dream (see "Self-questionnaires" section below). Moreover, they were asked if this dream was somewhat different 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 "Judge ratings" section below).

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 record 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, 1958). Sleep stages were manually scored according to the AASM criteria (Iber, Ancoli-Israel, Chesson, & Quan, 2007).

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 trough a pair of conductive rubber electrodes (4 cm x 3 cm), that were put inside into 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 studes, 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 by using an adhesive tape.

During the tDCS stimulation night, the direct current of 1 mA was delivered for 10 minutes with a fade-in period of 10 s. If during the stimulation the participant has been awakened or entered Stage 2, the stimulation was discontinued and resumed only if the same REM period had continued. During the sham stimulation night, 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).

Self-questionnaires

Four questionnaires were administered to the participants prior to the first night: the Landecker Inventory of Sleep Disorders (LISST; Weeß, Schürmann, & Steinberg, 2002), the dream questionnaire, the short version of metacognitions questionnaire (MKF-30; Arndt, Patzelt, Andor, Hoyer, & Gerlach, 2011) and the questionnaire of dispositional self-awareness (SAM, Filipp & Freudenberg, 1989).

LISST consists of 75 items and was constructed as a screening instrument to detect different sleep disorders. The items follow a 6-point Likert scale format (1 - never, 2 - rarely, 3 - sometimes, 4 - often, 5 - very often, 6 - always). Sufficient internal consistencies as well as accurate discrimination of patients with sleep disorders have been demonstrated (Weeß et al., 2002).

The dream questionnaire included questions on dream and lucid dream recall frequency during the past 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). In order to obtain units of mornings per week, the scale was recoded using the class means (0 → 0, 1 → 0.125, 2 → 0.25, 3 → 0.625, 4 → 1.0, 5 → 3.5, 6 → 6.5). The frequency of lucid dreams was measured on a 8-point scale (0 - never, 1 - less then 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). In order to obtain units in frequency per month, the scales were recoded using the class means (0 → 0, 1 → 0.042, 2 → 0.083, 3 → 0.25, 4 → 1.0, 5 → 2.5, 6 → 4.0, 7 → 18.0) (Schredl & Erlacher, 2004).

MKF-30 is an adapted German version of the metacognitions questionnaire MCQ-30 (Wells & Cartwright-Hatton, 2004), which measures individual differences in metacognitive beliefs, judgements and monitoring tendencies. The questionnaire consists of 30 items scored on a 4-point Likert scale (1 - do not agree, 2 - agree slightly, 3 - agree moderately, 4 - agree very much) and has 5-factor structure (cognitive confidence, positive beliefs about worry, cognitive self-consciousness, negative beliefs about uncontrollability of thoughts and danger, and beliefs about need to control thoughts).

SAM is a German modification of the Self-Consciousness Scale (Fenigstein, Scheier, & Buss, 1975). It has 27 items scored on a 5-point scale (1 – very rarely, 2 – rarely, 3 – sometimes, 4 – often, 5 – very often). Differently from the original questionnaire, SAM has 2-factor structure: private self-consciousness and public self-consciousness (social anxiety subscale is omitted).

Upon each REM awakening after a dream report the participants were asked to evaluate the intensity of positive and negative emotions during the dream 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), which assess different types of metacognitive activities: choice, suddenly captured attention, focused attention, public self-consciousness and reflective awareness of own thoughts/feelings, own behaviour and external events.

DLQ was a specially 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), which 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).

Judge ratings

After dream reports were transcribed and permutated, they were scored by an external judge (who was unaware to 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 the waking life and also occurs in normal, everyday life; 2 – many elements of the waking life, but with unusual sequences and connections, yet realistic; 3 – one or two fantasy objects, bizarre connections or actions impossible in the waking life; 4 – frequent/numerous fantasy objects, bizarre connections or actions impossible in the waking life) and also a number of bizarre elements within the dream was calculated.

Statistical analysis

IBM SPSS Statistics 20 software was used for statistical analysis. Statistical tests were applied with alpha = .05. Student's paired T-test was used for comparison between 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.

Results

Nineteen participants, who completed the study, reported that they recall on average 4.32 ± 1.66 dreams per week. The average reported lucid dreaming frequency was 2.89 ± 5.47 lucid dreams per 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).

One hundred ten REM awakenings were made in total (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. Therefore, there was a trend for lower number of awakenings in the tDCS condition and awakenings were made significant later considering both average clock time and average 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.

Only once a lucid dream was recorded with LRLRLR eye signalling during REM sleep (tDCS night). Six tiems, one of tDCS cables got disconnected and only one side of DLPFC was stimulated. Tree times on those occasions no dream had been recalled and the rest three dream reports were excluded from comparative dream analysis.

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

	Sham			**tDCS**			**T**	**p-val (2-tailed)**
	M	**SD**	**Range**	**M**	**SD**	**Range**		
Number of awakenings	3.21	1.03	2 - 5	2.53	1.81	0 - 7	2.050	.055
Dream recall rate (%)	88.6	16.5	50 - 100	90.4	15.9	50 - 100	-0.368	.718
Unusual dream report rate (%)	20.3	31.2	0 - 100	25.9	35.4	0 - 100	-0.543	.595
Average awakening clock time	5:03	0:40	4:05 - 6:23	5:40	1:09	3:48 - 7:44	-2.280.	.038
Average awakening time since sleep onset	5:49	0:41	4:58 - 7:18	6:29	0:58	4:46 - 8:15	-2.659	.018

Comparison of dream report data for two conditions is provided in Table 2. Emotional tone was calculated as difference between positive and negative feelings (range from -3 to 3). On tDCS nights dream reports were significantly longer than on sham stimulation nights (word count: 159.9 ± 111.1 vs. 116.6 ± 70.7, p<.05). No differences were found in self-reported emotional tone of the dreams. According to the external judge ratings on tDCS nights in comparison to sham nights the dreams were significantly more lucid (0.396 ± 0.611 vs. 0.167 ± 0.365, p<.05) and more bizarre (1.929 ± 0.523 vs. 1.660 ± 0.513, p<.05), yet the average number of bizarre elements did not differ between the two conditions. Further analysis revealed that lucidity and bizarreness ratings depended on the dream length (correlations with dream word count: lucidity r=.206, bizarreness r=.344, number of bizarre elements r=.255, all p<.05). To control this variable, we computed regression analysis and then compared the residuals. When controlled for the dream length, differences on dream bizarreness disappeared, yet on tDCS nights dreams remained significantly more lucid in comparison to sham nights (mean residuals: 0.121 ± 0.571 vs. -0.060 ± 0.362 , p<.05).

Table 2. Comparison data on dream reports for two conditions (N=16 participants)

	Sham		**tDCS**		**T**	**p-value**
	M	**SD**	**M**	**SD**		
Word count	116.6	70.7	159.9	111.1	-2.829	.013*[a]
Emotional tone (self-reported)	0.510	0.741	0.318	1.114	0.590	.564[a]
External judge ratings *without* correction for dream length						
Lucidity	0.167	0.365	0.396	0.611	-2.300	.018*[b]
Bizarreness	1.660	0.513	1.929	0.523	-2.291	.037*[a]
Number of bizarre elements	0.219	0.415	0.242	0.393	-0.172	.866[a]
External judge ratings *with* correction for dream length						

Lucidity	-0.060	0.362	0.121	0.571	-1.959	.035*[b]
Bizarreness	-0.163	0.471	-0.002	0.494	-1.547	.143[a]
Number of bizarre elements	-0.032	0.400	-0.076	0.382	0.331	.746[a]

Note: *p<.05. [a]2-tailed test, [b]1-tailed test.

We did a factor analysis on both MACE and DLQ questionnaires for the whole set of dream report ratings collected. For MACE, two-factor structure emerged, explaining 54.6% of variance (Table 3). The first factor (F1) could be described as "metacognition with internal focus" and the second (F2) as "metacognition with external focus". Overal rating scores (averages) for both components were calculated.

Table 3. 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 behaviour	**.594**	.377
Awareness of external events	.096	**.775**

Note: Oblimin rotation with Kaiser normalisation; correlation between the factors .265.

For DLQ questionnaire, one main factor emerged, explaining 44.1% of variance (Eigenvalue=5.286), which suggests an underlying construct of "lucidity" (Table 4). For calculating the overall lucidity rating score, two items with lowest loadings (No. 7 and 12) were excluded. Notably, those two items dealt with recall of waking facts, episodes or intentions. The overall DLQ lucidity score correlated positively with MACE "metacognition with external focus" subscale (r=.212, p=.018, 1-tailed), but not with MACE "metacognition with external focus" subscale (r=.086, p=.200, 1-tailed).

Table 4. 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 are not real people	**.872**
4. I deliberately chose one action instead of the other	**.417**
5. I was aware that all dream objects are 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. flied, 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 what I wanted to do in a lucid dream	.225

The comparison between both questionnaire scores for two conditions is provided in Table 5. The total lucidity score was higher in tDCS nights in comparison with sham stimulation nights (4.875 ± 7.487 vs. 3.426 ± 5.075, p=.05). In tDCS condition, the participants were also more aware that dream objects are not real (p<.05) and there were also strong tendencies for them to be more aware that their physical body is asleep, that dream characters are not real people and to make more choices (all p<.1).

Table 5. Comparison of questionnaire ratings for two conditions for all participants (N=16)

	Sham		**tDCS**		**T**	**p-value**
	M	**SD**	**M**	**SD**		**(1-tailed)**
MACE						

Making choice	0.901	0.738	1.118	0.680	-1.444	.085+
Attention captured suddenly	1.057	0.907	1.016	1.081	0.119	.547
Focused attention	1.426	1.235	1.231	1.358	0.733	.763
Public self-consciousness	0.870	1.093	0.981	1.175	-0.536	.300
Awareness of own thoughts/feelings	0.976	0.944	1.015	1.019	-0.160	.438
Awareness of own behaviour	1.440	1.231	1.591	1.358	-0.674	.256
Awareness of external events	1.347	1.225	1.644	1.039	-1.087	.147
OVERAL – Metacognition with internal focus (average)	1.123	0.803	1.187	0.860	-0.696	.249
OVERAL – Metacogntion with external focus (average)	1.202	0.937	1.330	0.914	-0.463	.325
DLQ						
1. I was aware that I was dreaming	0.560	1.028	0.656	1.274	-0.694	.249
2. I was aware that my physical body was asleep	0.369	0.889	0.625	1.218	-1.584	.067+
3. I was aware that all my dream characters are not real people	0.365	0.830	0.797	1.418	-1.531	.074+
4. I deliberately chose one action instead of the other	0.769	1.191	0.823	0.963	-0.181	.430
5. I was aware that all dream objects are not real	0.292	0.769	0.719	1.341	-1.893	.039*
6. I changed dream events in the way I wanted	0.517	0.882	0.510	1.121	0.047	.519
7. I recalled some facts or episodes from my waking life	1.407	1.250	1.284	1.100	0.682	.747
8. I changed dream characters in the way I wanted	0.085	0.203	0.313	0.772	-1.151	.134
9. I broke the physical laws of the waking reality (e.g. flied, went through a wall)	0.238	0.562	0.161	0.388	0.456	.673
10. I changed the dream scene in the way I wanted	0.139	0.270	0.177	0.410	-0.618	.273
11. I thought about different possibilities of what can I do in a dream	0.094	0.272	0.094	0.272	0.000	.500
12. I clearly remembered my intentions what I wanted to do in a lucid dream	0.000	0.000	0.031	0.125	-1.000	.167
OVERAL – Lucidity (average)	0.343	0.507	0.488	0.749	-1.759	.050*

Note: *p<.05, +p<.1. Total lucidity score does not include items 7 & 12.

Further, we analyzed separately two subgroups: (1) frequent lucid dreamers and (2) infrequent or non-lucid dreamers. Each subgroups consisted of 8 participants. On tDCS nights, in comparison with sham nights, frequent lucid dreamers (Table 6) had significantly higher scores on overall lucidity, awareness that that their physical body is asleep, that dream object are not real and that dream characters are not real people (all p<.05). In contrast, infrequent and non-lucid dreamers (Table 7) had no differences on any of lucidity ratings, but were making more choices (including a tendency to make more deliberate choices) on tDCS stimulations nights.

Table 6. Comparison of questionnaire ratings for two conditions for frequent lucid dreamers (N=8)

	Sham		**tDCS**		**T**	**p-value (1-tailed)**
	M	**SD**	**M**	**SD**		
MACE						
Making choice	1.167	0.818	1.152	0.722	0.081	0.531
Attention captured suddenly	0.990	0.618	1.552	1.238	-1.058	0.163
Focused attention	1.946	1.417	1.963	1.259	-0.054	0.479
Public self-consciousness	1.302	1.333	1.295	0.892	0.031	0.512
Awareness of own thoughts/feelings	0.733	0.818	1.196	0.582	-1.307	0.116
Awareness of own behaviour	1.879	1.237	1.807	1.282	0.200	0.576
Awareness of external events	1.558	1.097	1.662	0.932	-0.218	0.417
OVERAL – Metacognition with internal focus (average)	1.405	0.812	1.482	0.815	-0.496	0.318
OVERAL – Metacogntion with external focus (average)	1.274	0.664	1.607	0.996	-0.690	0.256
DLQ						
1. I was aware that I was dreaming	1.058	1.290	1.313	1.580	-0.957	0.185

2. I was aware that my physical body was asleep	0.592	1.227	1.250	1.512	-2.767	0.014*
3. I was aware that all my dream characters are not real people	0.583	1.137	1.594	1.690	-2.077	0.038*
4. I deliberately chose one action instead of the other	1.225	1.505	1.063	1.178	0.276	0.605
5. I was aware that all dream objects are not real	0.542	1.053	1.438	1.635	-2.285	0.028*
6. I changed dream events in the way I wanted	0.971	1.080	1.021	1.449	-0.186	0.429
7. I recalled some facts or episodes from my waking life	1.950	1.446	1.777	1.225	0.507	0.686
8. I changed dream characters in the way I wanted	0.171	0.268	0.625	1.026	-1.165	0.141
9. I broke the physical laws of the waking reality (e.g. flied, went through a wall)	0.475	0.740	0.323	0.513	0.443	0.665
10. I changed the dream scene in the way I wanted	0.246	0.349	0.354	0.538	-0.905	0.198
11. I thought about different possibilities of what can I do in a dream	0.125	0.354	0.188	0.372	-0.314	0.382
12. I clearly remembered my intentions what I wanted to do in a lucid dream	0.000	0.000	0.063	0.177	-1.000	0.176
OVERAL – Lucidity (average)	0.599	0.626	0.917	0.881	-2.318	0.027*

Note: *p<.05. Total lucidity score does not include items 7 & 12.

Table 7. Comparison of questionnaire ratings for two conditions for infrequent and non-lucid dreamers (N=8)

	Sham		**tDCS**		**T**	**p-value (1-tailed)**
	M	**SD**	**M**	**SD**		
MACE						
Making choice	0.635	0.581	1.083	0.684	-2.058	0.040*
Attention captured suddenly	1.125	1.171	0.479	0.559	1.749	0.938
Focused attention	0.906	0.801	0.500	1.069	0.928	0.808
Public self-consciousness	0.438	0.596	0.667	1.392	-0.654	0.267
Awareness of own thoughts/feelings	1.219	1.051	0.833	1.345	1.415	0.900

Awareness of own behaviour	1.000	1.130	1.375	1.485	-1.428	0.098
Awareness of external events	1.135	1.382	1.625	1.201	-1.710	0.066
OVERAL – Metacognition with internal focus (average)	0.840	0.735	0.892	0.849	-0.463	0.329
OVERAL – Metacogntion with external focus (average)	1.130	1.196	1.052	0.788	0.277	0.605
DLQ						
1. I was aware that I was dreaming	0.063	0.177	0.000	0.000	1.000	0.825
2. I was aware that my physical body was asleep	0.146	0.274	0.000	0.000	1.507	0.913
3. I was aware that all my dream characters are not real people	0.146	0.274	0.000	0.000	1.507	0.913
4. I deliberately chose one action instead of the other	0.313	0.547	0.583	0.684	-1.786	0.059+
5. I was aware that all dream objects are not real	0.042	0.118	0.000	0.000	1.000	0.825
6. I changed dream events in the way I wanted	0.063	0.177	0.000	0.000	1.000	0.825
7. I recalled some facts or episodes from my waking life	0.865	0.764	0.792	0.733	0.490	0.681
8. I changed dream characters in the way I wanted	0.000	0.000	0.000	0.000	-	-
9. I broke the physical laws of the waking reality (e.g. flied, went through a wall)	0.000	0.000	0.000	0.000	-	-
10. I changed the dream scene in the way I wanted	0.031	0.088	0.000	0.000	1.000	0.825
11. I thought about different possibilities of what can I do in a dream	0.063	0.177	0.000	0.000	1.000	0.825
12. I clearly remembered my intentions what I wanted to do in a lucid dream	0.000	0.000	0.000	0.000	-	-
OVERAL – Lucidity (average)	0.087	0.101	0.058	0.068	0.678	0.741

Note: *p<.05, +p<.1. Overall lucidity score does not include items 7 & 12.

Discussion

TDCS stimulation over the DLPFC during REM sleep resulted in increased dream lucidity both according to the self-ratings of participants and to the external rating of a "blinded" judge and therefore our results provide empirical support for the involvement of the DLPFC in lucid dreaming. The effects however were not very strong and 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. It is likely that activation of a wider network of different brain areas is needed to achieve lucidity in dreams. For example, Dresler with colleagues (2012) found an increased activation during REM lucid dreams not only in the prefrontal, but also occipito-temporal cortices, bilateral precuneus, cuneus and parietal lobules. These brain areas can also be targeted to stimulate lucid dreaming. On another hand, a combined tDCS and PET of regional cerebral blood flow (rCBF) study by Lang et al (2005) found that both cathodal and anodal tDCS induced increases and decreases in rCBF not only in the cortical areas underneath the electrodes, but also in a much wider network of cortical and subcortical areas. Therefore it is possible that not only the DLPFC but also some other brain regions had been also activated due to the stimulation. Furthermore, the activation itself might not have reached a sufficient threshold to induce lucidity. For example, Baudewig, Nitsche, Paulus and Frahm (2001) in 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 5% unsignificant increase. 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 comparing to 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. Therefore the number of awakenings seemed to be lower on tDCS nights (for three participants no awakenings even were possible) and awakenings were carried out later. This also explains the longer dream reports for the tDCS nights: If the stimulation awakened a participant, it was discontinued and reapplied if the participant will re-enter REM sleep. Therefore the participants might have spent more time in REM sleep during the tDCS nights. Other study which applied tDCS during REM also reported cases where the stimulation will disrupt 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, which indicates some itching sensations. To eliminate those sensations, in future studies topically applied local anaesthetic cream, such as EMLA, can be used (McFadden, Borckardt, George, & Beam, 2011).

The finding that infrequent and non-lucid dreamers were making more choices in their dreams on tDCS night 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 increased awareness that their physical body is asleep and that their dream characters and dream objects are not real. DLPFC is known to play an crucial role in working memory (Curtis & D'Esposito, 2003), which is necessary to recognize and maintain the awareness of the dream state and its illusory nature. Furthermore, Lau and Passingham (2006) demonstrated that of all brain regions, the DLPFC is exclusively associated with conscious perception, which is of course the cornerstone of lucidity in dreams.

Although dreams from tDCS nights were scored to be not only more lucid, but also to be more bizarre, the difference in bizarreness disappeared when we controlled for the dream length. Conversely, the linkage between dream lucidity and bizarreness was also found in previous studies (e.g. McCarley & Hoffman, 1981). In this study we 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 (cf. Purcell, Mullington, Moffitt, Hoffmann, & Pigeau, 1986), therefore metacognitive activities with external (environmental) focus might play a more important role in lucid dreaming.

In summary, this study provides the direct empirical evidence for the involvement of the DLPFC in lucid dreaming. While this causal connection is important on the neurophysiological level, due to the small effects it does not appear to be a promising tool for lucid dream induction on a practical level (cf. Noreika et al., 2010). For practical purposes, other lucid dream induction methods can be suggested (see Stumbrys, Erlacher, Schädlich, & Schredl, 2012).

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Appendix to the Progress Report of the study entitled “Lucid dream induction by transcranial cortex stimulation: A test of the prefrontal hypothesis of lucid dreaming”
funded by the BIAL Foundation (Grant 712/10)

Participant	Night No	Date	Awake-nings	Dreams recalled	Comments
T1	1	16.11.2011	1	1	- Tested the whole procedure for the first time - Very poor sleep with very little REM, only one awakening was possible - Problem with tDCS electrodes (cables got disconnected) - Tested questionnaires
T2	1	01.12.2011	2	1	- Successful replication of the procedure - The cable problem identified and fixed - Lucidity signal (LRLRLR) in the first REM - tDCS electrode fastening problem identified and fixed afterwards (elastic bandage changed to a tubular net cap)
P1	1	20.01.2012	0	-	
P1	2	21.01.2012	5	4	Sensitivity issue (stimulation disrupts REM sleep)
P1	3	22.01.2012	5	4	
P2	1	10.02.2012	0	-	
P2	2	11.02.2012	3	3	
P2	3	12.02.2012	4	3	
P3	1	27.02.2012	0	-	
P3	2	28.02.2012	2	1	
P3	3	29.02.2012	3	2	
P4	1	02.03.2012	0	-	
P4	2	03.03.2012	3	2	Sensitivity issue
P4	3	04.03.2012	4	3	
P5	1	07.03.2012	0	-	
P5	2	08.03.2012	3	3	Sensitivity issue
P5	3	09.03.2012	4	3	
P6	1	12.03.2012	0	-	
P6	2	13.03.2012	2	2	Sensitivity issue (strong)
P6	3	14.03.2012	1	1	
P7	1	18.03.2012	0	-	Withdrawn after the first night due to sensitivity issue
P8	1	11.04.2012	0	-	Saline was started to use instead of water to soak the sponges for tDCS electrodes
P8	2	12.04.2012	4	4	
P8	3	13.04.2012	5	4	
P9	1	16.04.2012	0	-	
P9	2	17.04.2012	4	4	
P9	3	18.04.2012	7	7	
P10	1	20.04.2012	0	-	
P10	2	21.04.2012	2	2	Sensitivity issue
P10	3	22.04.2012	4	4	
P11	1	08.05.2012	0	-	
P11	2	09.05.2012	2	2	Very strong sensitivity issue – no REM awakening could be done on the stimulation night
P11	3	10.05.2012	0	-	
P12	1	12.05.2012	0	-	
P12	2	13.05.2012	0	-	Very strong sensitivity issue – no REM awakening could be done on the stimulation night
P12	3	14.05.2012	3	3	
P13	1	21.05.2012	0	-	

P13	2	22.05.2012	2	2	Sensitivity issue
P13	3	23.05.2012	2	2	
P14	1	27.05.2012	0	-	
P14	2	28.05.2012	1	1	Sensitivity issue
P14	3	29.05.2012	2	1	
P15	1	15.06.2012	0	-	Withdrawn after the first night due to sensitivity and having very little REM sleep
P16	1	20.06.2012	0	-	
P16	2	21.06.2012	3	3	LRLRLR signal during NREM; another LRLRLR during REM and confirmed lucidity
P16	3	22.06.2012	3	3	
P17	1	24.06.2012	0	-	
P17	2	25.06.2012	0	-	Withdrew after the second night as being not able to sleep in the sleep laboratory
P18	1	22.07.2012	0	-	
P18	2	23.07.2012	3	2	
P18	3	23.07.2012	3	3	
P19	1	29.07.2012	0	-	
P19	2	30.07.2012	2	2	Sensitivity issue
P19	3	31.07.2012	2	2	
P20	1	03.08.2012	0	-	
P20	2	04.08.2012	0	-	Very strong sensitivity issue – no REM awakening could be done on the stimulation night
P20	3	05.08.2012	3	3	
P21	1	08.08.2012	0	-	
P21	2	09.08.2012	5	5	
P21	3	10.08.2012	3	3	
P22	1	12.08.2012	0	-	Withdrawn after the first night due to sensitivity issue
P23	1	22.08.2012	0	-	
P23	2	23.08.2012	3	3	Sensitivity issue
P23	3	24.08.2012	2	2	