A pilot investigation into brain-computer interface use during a lucid dream

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Summary. During lucid moments of a dream, the sleeper is aware of the dream as it is occurring, and as a result can often perform predetermined actions within the dream. This provides a unique opportunity for dream research, as lucid dreamers can send real-time signals from sleep to the external world. Historically, such sleep-to-wake communication from a lucid dream is executed via left-right eye movements, which places hard limitations on information transfer. Recent advances in biomedical equipment — specifically brain-computer interfaces — have resulted in headsets that use neural recordings to translate mental imagery into computer commands. In light of evidence suggesting that dreamed and imagined actions recruit similar neural resources, I considered the possibility that the same mental commands that are collected and translated from waking imagery could be similarly performed and detected from within a lucid dream. In this exploratory study with proof-of-concept intent, three participants were asked to use an Emotiv EPOC+ headset and companion software to map a mental motor command (pushing a block) with a resulting computer action (graphic of block moving forward). After waking training, participants attempted to induce a lucid dream while wearing the headset, and upon lucidity perform the same mental command. In two participants, subjectively reported lucid dream task completion was corroborated with video footage of the resulting computer graphic. These preliminary results suggest that a wake-trained brain-computer interface can be controlled from sleep and offer important directions for future dream communication and research.

Keywords: lucid dreaming, sleep, two-way communication, BCI, mental imagery

1. Introduction

During a lucid dream, the (lucid) dreamer is aware of the dream state as it is occurring (Baird et al., 2019; LaBerge et al., 1981). This awareness of the dream state often coincides with some level of volitional control over dream content and actions (Dresler et al., 2014; Stumbrys et al., 2014). The ability of a participant to perform specific actions within the dream led to the initial objective verification of lucid dreaming (Hearne, 1978; LaBerge et al., 1981). Eye movements and fist clenches within the dream have predictable and measurable external physiological correlates, which were used to send predetermined signals from a sleeping participant to the experimenter (detected via polysomnography). This method of communicating from a dream with left-right-left-right (LRLR) eye signals has become the de-facto standard for timestamping the moment of lucidity during relevant experiments (Baird et al., 2019) and has also been used as a method of communicating to the researcher in real-time from sleep (Appel, 2013; Konkoly & Paller, 2019, see also Fenwick et al., 1984).

However, this method of communication has limitations. Sending signals with eye movements or muscle clenches places a hard limitation on the amount of information that can be sent over a limited time. Participants with knowledge of Morse code have communicated from sleep by using left/right muscle clenches or eye movements as long/short tones to represent letters (Appel, 2013; LaBerge et al., 1981). While allowing for more complex signaling, this method's shortcoming is the length of time required to send a message. The duration of lucidity is limited, and thus Morse code messages from a lucid dream are typically restricted to just a few letters. A survey study found that participants reported an average estimated duration of about 14 minutes for their home lucid dreams (Stumbrys et al., 2014), although this might not be the same for laboratory lucid dreams. Further, Morse code is not a common language and requires significant effort for the participant to learn. More advanced eye-tracking methods have found that specific shapes can be drawn with orchestrated eye movement patterns (LaBerge et al., 2018), but it is unclear if this can serve as an effective real-time communication system (although see Appel, 2019). Thus, current sleep-to-wake signaling methods are largely limited to binary messages or numbers (e.g., x amount of eye movements). The limitations of these signaling methods hinder research and the development of applications that utilize sleep-to-wake communication (Appel et al., 2018). Here, I propose a proof-of-concept for a communication method that could overcome these current limitations.

Current sleep-to-wake communication methods are effective in-so-far-as (lucidly) dreamed actions share a similar physiology as waking actions and imagery (Dresler et al., 2011; Erlacher & Schredl, 2008). The notion that imagined actions recruit similar neural resources as waking is also a key premise behind brain-computer interface (BCI) technol-

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ogy (Chaudhary et al., 2016; Lebedev & Nicolelis, 2006). BCIs recording neural signals from motor cortex have allowed clinically immobilized patients to control robotic arms or other digital computer signals using only mental imagery or movement intentions (Wolpaw et al., 2002). Most lucid dreams occur in rapid eye movement sleep (LaBerge, 1988; LaBerge et al., 1986), at which stage muscle atonia increases motor neuron inhibition, effectively paralyzing the sleeper with the exception of eye movements and muscle twitches (Chase & Morales, 1990). Therefore, a clinically immobilized patient and an actively lucid dreaming participant might be in a similar situation of being both conscious of their waking body and fully intent on moving their limbs, despite being unable to do so. Accordingly, I hypothesized that due to the ability of a lucid dreamer to perform predetermined actions during a dream and the neural overlap between waking and lucidly dreamed actions, a BCI that could be successfully controlled during waking could be similarly controlled during a lucid dream.

Experienced lucid dreaming participants were recruited to test this hypothesis in an exploratory pilot study. For each participant, a consumer-grade BCI (Emotiv EPOC+) was trained to distinguish between the presence and absence of a specific mental imagery task, and then upon lucidity the same mental task was performed. All participants subjectively reported performing the task during a lucid dream, as indicated by written dream reports and lucidity-focused questionnaires. When participants were asleep but not performing the task, the BCI showed little detection of the task. Importantly, when participants performed the task during a lucid dream (prefaced with LRLR eye movements), the BCI showed increased task detection levels.

Due to low-quality equipment and lack of access to the BCI's algorithms, this preliminary investigation warrants scrutiny and further verification. Yet, the results suggest that a BCI trained on a waking mental imagery task can then be controlled during sleep by performing the same task when volition reappears in lucid dreaming. While the current study focused on BCI detection of a single command, the rapid development and potential of BCI research suggest that BCI technology could offer a solution to existing sleep-to-wake communication limitations.

2. Methods

2.1. Participants

Three experienced lucid dreamers (reporting successful lucid dream induction in >25% of attempts) participated in the current pilot study. All participants were recruited via personal contact except sub-001 (the author). All participants were male between the ages of 25 and 35 years (sub-001=26, sub-003=25, sub-004=35). One volunteer (sub-002) dropped out after consent and did not follow through with any steps of participation. Participant sub-001 reported completing the task, but due to a computer malfunction (no data was recorded during the sleep session) is not included in analyses (but dream report and questionnaires are included in SI). Participant sub-003 was a narcoleptic. Narcoleptics show an increased tendency towards lucidity during dreams (Dodet et al., 2015; Rak et al., 2015) and are increasingly used in lucid dreaming research (e.g., Oudiette et al., 2018). Research was performed in accordance with the University of Missouri Institutional Review Board.

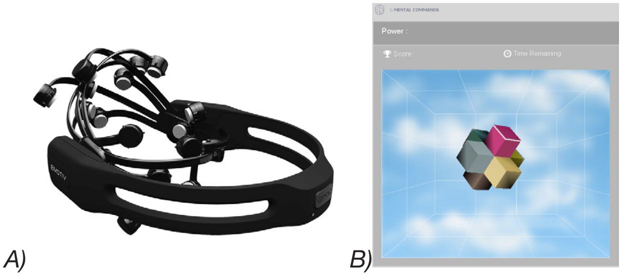


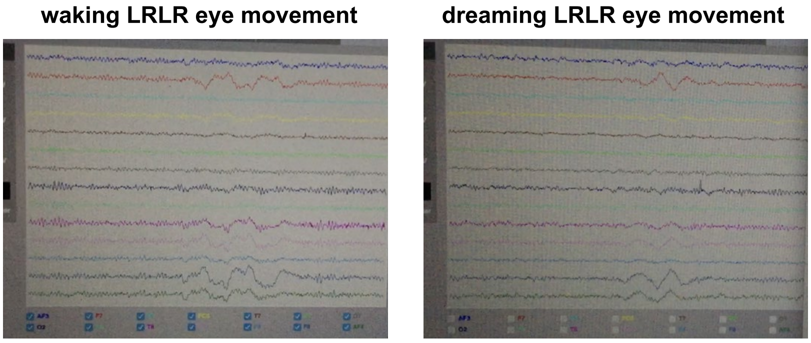
Figure 1. A) Emotiv EPOC+ headset. Participants were able to sleep with the headset on by lying on their backs and without support under the upper half of the head. B) Emotiv Controlpanel software. The mental block-pushing task (MBPT) involves imagining this virtual block moving forward (i.e., deeper) into the screen. During training, the block animates moving forward while the participant performs the MBPT. During testing, the block only animates when the headset detects the MBPT.

2.2. Brain-computer interface

The BCI setup was an Emotiv EPOC+ headset (Figure 1A) and companion software (Xavier Controlpanel 3.0.0.44; Xavier TestBench 3.0.0.37) running on a Macbook Pro laptop. The Emotiv EPOC+ is a 14-channel mobile electroencephalograph (EEG) system designed to maximize efficacy, mobility, and affordability while maintaining a level of reliability near laboratory-grade EEG systems (Badcock et al., 2013; Bobrov et al., 2011; De Vos et al., 2014; Debener et al., 2012; Taylor & Schmidt, 2012; Zich et al., 2015). The EPOC+ responds to 0.16-43 Hz using 14 (plus 2 reference) saline-soaked sensors at the following electrode locations: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 (references at left/right mastoids). The main feature of the Emotiv EPOC+ is the ability to build an EEG classifier that detects the intention of moving a virtual block and displays a corresponding graphic upon intention detection. The general layout for training and testing the EPOC+ is 1) a virtual block is displayed in the middle of the computer screen (Figure 1B), 2) a resting state, or non-task, EEG signal is collected under a neutral label, 3) EEG data is collected under a push label while the user performs a mental block-pushing task (MBPT), 4) after steps 2 and 3 are repeated, the user only has to perform the MBPT and the virtual block will move forward (i.e., push) in response. One potential challenge in the current design was that the back of the EPOC+ headset protrudes a few inches, possibly making it difficult to wear while sleeping. However, slight modifications such as the addition of neck support enabled the EPOC+ to be used during sleep. Battery life of the EPOC+ is reported as greater than 6 hours using wireless connectivity (Bluetooth), which was ample time for the current study design.

2.3. Lucid dream induction technique

The study was designed such that participants could employ their preferred lucid dream induction technique (Price & Cohen, 1988; Stumbrys et al., 2012). Accordingly, the EPOC+ was applied either preceding an afternoon nap (sub-003) or during the morning/awake period of a wake-back-to-bed (WBTB; sub-001 and sub-004). WBTB is a common lucid



waking LRLR eye movement

dreaming LRLR eye movement

Figure 2. LRLR eye movements. Screenshots of what LRLR eye movements look like when performed during waking (left) and during a lucid dream (right). These are from participant sub-003, see Figure S1 for sub-004.

dream induction technique that involves waking up after about five hours of sleep, staying awake for 10-90 minutes, and returning to bed with the intention of having a lucid dream (LaBerge, 1980; Stumbrys et al., 2012). The potential lucid dream generally occurs anywhere from sleep onset to one hour into the second sleep period.

2.4. General procedure

Participants completed a training phase of approximately 45 minutes during wake where they learned to push a virtual block with mental effort, followed by a test phase where they tried to induce a lucid dream and push the same virtual block during sleep. The goal of the training phase was to train the BCI on the distinction between a participant performing the MBPT and rest. The goal of the testing phase was to establish whether the same MBPT could be performed and detected during a lucid dream. Participants were allowed to complete a train-test sequence on multiple occasions. Because participants varied in their specific protocols as a result of different lucid dream induction techniques, the details of their procedures varied and are included in the Results section.

2.5. Training phase

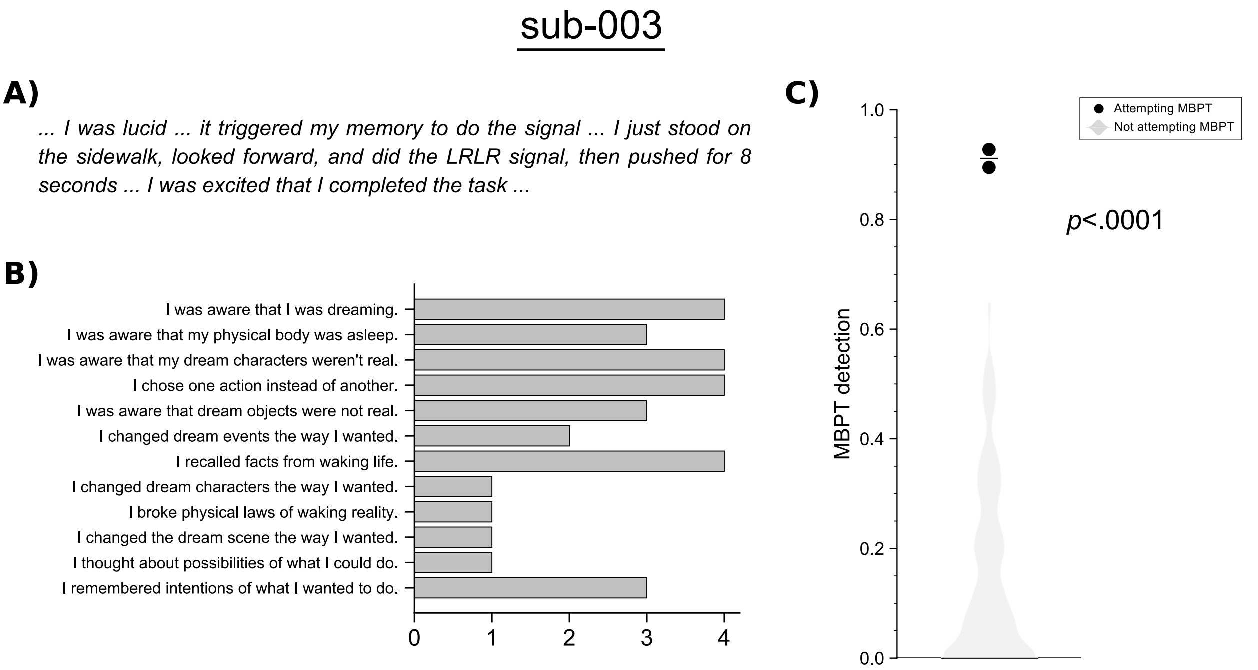
After the BCI was properly set up on the participant, the BCI was trained on the MBPT. The participant was instructed to alternate performing the MBPT and a resting task for 8-second segments while EEG was recorded and mapped to Emotiv software labels push and neutral, respectively. For the MBPT, the participant was told: “Imagine pushing the block – however you choose to imagine it, all that matters is that the thought is consistent.” For the resting task, the participant was told: “Clear your head.” These instructions were a subtly modified version of those provided by Emotiv. Participants alternated between MBPT and rest mappings until they passed a qualitative evaluation of successful training. To evaluate BCI training, the participant again alternated between the MBPT and rest, but here the BCI only measured EEG and decoded the participant’s thought process (MBPT vs. rest). If perfectly trained, the block graphic would move forward only and always during the MBPT, indicating 100% decoding accuracy. This verification step was completed intermittently throughout the training phase until the BCI could accurately detect the MBPT on ~70% of attempts.

2.6. Testing phase

The testing phase consisted of the participant falling asleep with the BCI on, attempting to induce a lucid dream, and upon lucidity repeating the same MBPT they performed during training. As is customary in lucid dreaming studies, each participant was asked to first confirm the lucid dream state with a LRLR eye signal (Figure 2) before attempting the experimental task (Baird et al., 2019). This signal also serves to timestamp the beginning of dream task execution. Each participant was asked to repeat a sequence of the LRLR signal and 8-10 seconds of the MBPT as many times as possible once lucid in the dream. Computer activity showing both EEG and virtual block activity was recorded and reviewed offline. Immediately upon awakening, participants were asked to complete a custom waking survey that included a written dream report, specific questions about the MBPT and LRLR signaling, the Dream Lucidity Questionnaire (DLQ; Stumbrys et al., 2013) and the Lucidity and Consciousness in Dreams scale (LuCiD; Voss et al., 2013).

2.7. Analysis

Emotiv does not offer access to their machine learning algorithms or classifier decision output. To quantify the BCI’s detection of the MBPT during sleep, the testing phase video was separated into 8-second segments centered around the first LRLR eye signal, and within each segment the “MBPT detection” score is the proportion of time that the display showed MBPT detection. To evaluate the ability of the BCI to detect the MBPT performed during a lucid dream, the MBPT detection scores during reported lucid dream MBPT completion were compared against all other MBPT detection scores (i.e., those from segments during sleep that the participant did not report performing the MBPT). Instructions to the participants were to attempt the MBPT during lucidity for 8-10 seconds after LRLR signaling, but to account for possible time discrepancies between lucid dreaming and waking (Erlacher et al., 2014), MBPT detection scores of the two segments following LRLR signaling were averaged, resulting in a single MBPT detection score to be compared against all others. The p-values were calculated as the proportion of null distribution MBPT detection scores that were greater than the single MBPT detection score from the lucid dream MBPT completion. Each participant’s empirical null distribution was bootstrapped by resampling with replacement 10000 times from all MBPT detection scores outside of the lucid dream MBPT completion.



... I was lucid ... it triggered my memory to do the signal ... I just stood on the sidewalk, looked forward, and did the LRLR signal, then pushed for 8 seconds ... I was excited that I completed the task ...

Figure 3. Results from sub-003 lucid dream MBPT task completion. A) Dream report. Excerpts from the dream report indicate lucidity and task completion (full dream report in Figure S4). B) DLQ scores. Likert responses upon awakening qualitatively indicate clear lucidity during the dream (LuCiD scores in Figure S3). C) BCI detection during sleep. MBPT performed during dreaming is easily detectable with a wake-trained BCI. See Analysis section for description of the MBPT detection measure. Horizontal bar is the mean MBPT detection score of the two segments following LRLR signaling (see video excerpt of task completion during sleep: https://osf.io/ane86/).

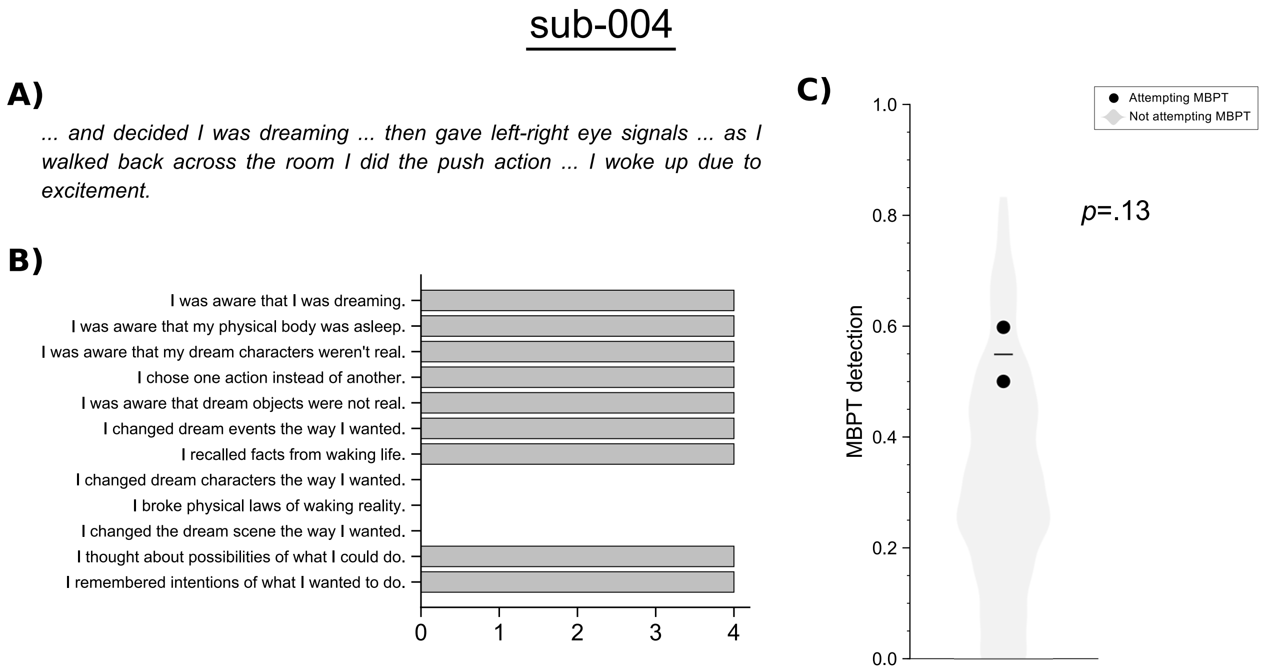
This analysis was performed individually on each test phase where the participant reported completing the MBPT during a lucid dream. Analyses were performed using NumPy (Oliphant, 2006) and Pandas (McKinney, 2010) in an IPython (Perez & Granger, 2007) environment. Data visualizations were performed using Matplotlib (Hunter, 2007).

3. Results

After waking training, the BCI was able to reliably detect the MBPT within each participant. In a following sleep session, participants were asked to become lucid while dreaming and then perform the same MBPT after a LRLR eye signal. To evaluate whether the BCI detected this task during sleep, MBPT detection scores from the time of lucid dream task completion were compared against the MBPT scores of all other sleep segments. Two participants successfully induced a lucid dream and self-reported performing the MBPT task after LRLR eye signaling while video was being recorded. Objective evidence corroborating task completion was present with one participant, while the other showed mild evidence, together suggesting proof-of-concept support for BCI communication from a lucid dream. The results from each of these two cases are reported separately below.

Participant sub-003 reported frequently becoming lucid during afternoon naps, and so performed the experiment during two afternoon sessions. During the first session sub-003 reported becoming lucid but not performing the MBPT during the dream, and so returned for a second session. Participant sub-003 completed the training phase in a simulated sleep position in the hopes to mimic the test phase as much as possible. This consisted of lying down in the expected sleeping position (on back) with eyes closed and lights off. On the second train-test sequence, the training phase was stopped after approximately 30 minutes because the BCI was well-trained, as indicated by the small 95% confidence interval of the null distribution ([0,.52]; Figure 3C; see also verification video clip: https://osf.io/2gctz/). Because all MBPT detection scores in the null distribution come from segments during sleep where the MBPT was not being performed, the spread of this distribution is a measure of how well the BCI was trained (where higher spread implies poorer training). Training was followed immediately by a nap and lucid dream MBPT attempt. During this nap, sub-003 reported successfully becoming lucid and completing the MBPT during the lucid dream (Figure 3A). DLQ scores indicate clear subjective lucidity (Figure 3B). Participant sub-003 reported attempting the task twice consecutively upon lucidity, and the averaged MBPT score of the two segments following LRLR signaling was far outside the null distribution of non-task relevant MBPT test scores (.91, p<.0001; Figure 3C; see video clip of MBPT during lucid dream: https://osf.io/ane86/).

Participant sub-004 performed the training phase while sitting upright at a desk, directly in front of the laptop. The training phase in total took approximately 90 minutes (with breaks) because there was less success in training the BCI (null distribution confidence interval = [0,.76]; Figure 4C), possibly due to a weaker headset (Bluetooth) connection. Participant sub-004 went to sleep according to their regular nightly schedule, but woke up approximately five hours after sleep, performed the training phase, and then returned to sleep. Participant sub-004 reported becoming lucid and completing the MBPT once following LRLR signaling during a lucid dream (Figure 4A), and DLQ scores suggest the



... and decided I was dreaming ... then gave left-right eye signals ... as I walked back across the room I did the push action ... I woke up due to excitement.

Figure 4. Results from sub-004 lucid dream MBPT task completion. A) Dream report. Excerpts from the dream report indicate lucidity and task completion (full dream report in Figure S4). B) DLQ scores. Likert responses upon awakening qualitatively indicate clear lucidity during the dream (LuCiD scores in Figure S3). C) BCI detection during sleep. MBPT performed during dreaming is mildly detectable with a wake-trained BCI. See Analysis section for description of the MBPT detection measure. Horizontal bar is the mean MBPT detection score of the two segments following LRLR signaling.

dream was indeed lucid (Figure 4B). BCI detection analysis shows mild support for objective task detection (p=.13; Figure 4C) with a lucid dream MBPT detection score of 0.55 following LRLR eye signaling (onset of dream task).

4. Discussion

The present pilot data show preliminary evidence suggesting that BCIs developed for waking control with mental imagery (Chaudhary et al., 2016; Lebedev & Nicolelis, 2006; Wolpaw et al., 2002) can be similarly used from within a lucid dream. Three participants with high lucid dream induction success rates reported performing a specific mental task during a lucid dream in an attempt to activate a consumer-grade BCI that was trained on the same mental task during waking. Of the two participants whose data was successfully recorded through the sleep session, one showed clear evidence of the BCI detecting the task and the other showed mild evidence. The participant who showed less evidence also had lower signal quality during BCI training and testing. Importantly, this study includes many caveats and limitations and necessitates further investigations that involve more sophisticated BCI technology and analyses before drawing firm conclusions.

The BCI used in the current study was trained to distinguish only between the presence and absence of a single mental task (i.e., the MBPT), which offers no advancement beyond the already common LRLR eye signaling frequently used in the literature (Baird et al., 2019). This restriction was applied for pilot purposes, but if a single mental task can be detected, then increasing the range of detectable tasks should also be plausible. Such an increase in message options would provide a more efficient mode of communication from sleep to waking. With further verification of lucid dreaming BCI control, the improvement in communication abilities from a sleeping participant to a waking researcher is a promising application that could benefit both research and clinical fields (Appel et al., 2018).

For research, an increase in communication abilities would allow for live dream reporting rather than relying on waking dream recall (Windt, 2013), which has its own limitations (Rosen, 2013; Solomonova et al., 2014). Additionally, lucid dreaming offers a rare state of consciousness with its own neurophysiological signature (Dresler et al., 2012; Voss et al., 2009), and probing cognition during this state is an intriguing avenue of consciousness research (Appel et al., 2018; Baird et al., 2019; Windt & Noreika, 2011). Probing the lucid dreaming brain during sleep is a promising experimental approach (Appel, 2013; Appel & Pipa, 2017; Konkoly & Paller, 2019), and increasing response options from the dream with imagery and motor actions has the potential to increase experiment complexity. Furthermore, lucid dreaming has been consistently linked with creativity (Blagrove & Hartnell, 2000; Stumbrys & Daniels, 2010), but a recent suggestion is that creative solutions that occur during dreaming are less- or in-accessible upon awakening (Stumbrys & Daunytė, 2018). Being able to control computer signals from a dream – either to send messages or to directly control other tools – opens avenues for extracting that creativity.

BCI research is largely motivated by developing communication tools for those who are currently restricted by clinical conditions (Chatelle et al., 2012; Chaudhary et al., 2016; Luauté et al., 2015; Wolpaw et al., 2002) such as motor disorders (Bauer et al., 1979) or disorders of consciousness (Bernat, 2006; Owen, 2008). In extreme cases, it is unclear if such patients are conscious. Thus, a crucial line of research is to develop response options for immobilized patients (Chatelle et al., 2012; Monti et al., 2010; Owen et al., 2006, 2016). While patient populations are currently used in the development of BCI communication tools, these experiments are often unable to distinguish whether the patient is not conscious or just unable to control the BCI (Overgaard & Overgaard, 2011; Peterson et al., 2015). Most lucid dreams occur in REM sleep (LaBerge, 1988; LaBerge et al., 1986), which includes muscle atonia that prevents most overt motor actions (Chase & Morales, 1990). This physiological similarity suggests that lucid dreaming participants might serve as a viable model for developing methods to communicate with clinically immobilized patients.

Performing an action during a dream can itself be considered a form of mental imagery, since the entire experience is internally generated. Interestingly, it is also possible to use mental imagery within a lucid dream (Worsley, 1988; Zadra, 2016). This event is unique to the dream state in that there are two levels of internal representation involved; the dream character – already an internal representation – is able to generate another internal representation using mental imagery. In the current study, participants were instructed to use mental imagery for the MBPT during waking and then simply repeat the task during their lucid dream. Explicit instructions as to whether they should act out or imagine the MBPT during their dream wasn't specified, and which of these two alternatives they chose was unclear from initial dream reports (see SI for full dream reports). The prediction here that a BCI could be controlled during a lucid dream was based on research into the neural overlap between action, imagery, and lucid dream actions (Dresler et al., 2011), but future work might distinguish between the neural representations of lucid dream actions and lucid dream imagery.

Without proper polysomnography, it is not possible to objectively verify that participants were indeed asleep. That is, participants might have been awake – even without awareness of it (Campbell & Webb, 1981) – while performing the MBPT. This is unlikely given that all participants were experienced lucid dreamers and highly familiar with their sleep patterns/experiences. Further limitations include the use of consumer-grade BCI equipment and a proprietary decoding algorithm.

To my knowledge, the current pilot exploration is the first to demonstrate that a BCI trained on waking imagery can be controlled with similar intentions during a lucid dream. Aforementioned limitations and the use of only a few participants prevent strong inferences but indicate that further research should be conducted to evaluate whether BCIs will serve as an efficient mode of communication from sleep.

Supplementary Information

available at https://osf.io/7baw4/.

Resource availability statement

All data, code, and materials are available at the OSF project site https://osf.io/mr7hf/.

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Conflict of interest statement

No potential conflicts of interest are declared.

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