Highly effective verified lucid dream induction using combined cognitive-sensory training and wearable EEG: a multi-centre study

Mahdad Jafarzadeh Esfahani[1,†,*], Leila Anna Christina Salvesen[1,2,†], Claudia Picard-Deland[3,†], Tobi Matzek[3], Ema Demsar[4,5], Tinke van Buijtene[1,6], Victoria Libucha[1], Bianca Pedreschi[2], Giulio Bernardi[2], Paul Zerr[1], Nico Adelhöfer[1], Sarah Schoch[1], Michelle Carr[3,7], Martin Dresler[1]

[1] Donders Institute for Brain, Behaviour and Cognition, Radboudumc, The Netherlands

[2] Sleep, plasticity, and conscious experience group, MoMiLab Research Unit, IMT School for Advanced Studies Lucca, Lucca, Italy

[3] Dream Engineering Laboratory, Center for Advanced Research in Sleep Medicine, CIUSSS-NIM, Montreal, QC, Canada

[4] Monash Centre for Consciousness and Contemplative Studies, Melbourne, Australia

[5] Monash University, Department of Philosophy, Melbourne, Australia

[6] Music Technology Group, Universitat Pompeu Fabra, Barcelona, Spain

[7] Department of Psychiatry and Addictology, University of Montreal, Montreal, QC, Canada

[†] Equal contribution

[*] **Corresponding author:**

Mahdad Jafarzadeh Esfahani

Donders Institute for Brain, Cognition and Behaviour

Radboud University Medical Center

Kapittelweg 29

6525 EN, Nijmegen

The Netherlands

Email: mahdad.jafarzadehesfahani@donders.ru.nl

Abstract

The state of becoming aware that one is dreaming within an ongoing dream, referred to as lucid dreaming (LD), can occur spontaneously. Yet, since the occurrence of spontaneous LD is relatively rare, various methods have been proposed to induce LD. Existing scientific literature, however, has been constrained by either small sample sizes with limited generalizability, or by reliance on subjective measures without physiological signals. To address these limitations, we recorded verifiable LD using 2-channel EEG and an open-source dream engineering toolbox (Dreamento) in a large sample size of 60 participants collected across a multi-center study in the Netherlands (NL), Italy (IT), and Canada (CA). We employed a novel combination of the senses-initiated lucid dreaming (SSILD) method and a targeted lucidity reactivation (TLR) protocol. Our final sample consists of 60 participants who came twice to the lab for morning naps with a pre-sleep lucidity training paired with multimodal sensory cues (visual, auditory, tactile). Cues were presented again in REM sleep in one of the two naps (stimulation and sham conditions counterbalanced). This preprint reports results from NL and IT in 40 participants: we successfully induced signal-verified lucid dreams (SVLD) in 65% and 45% of NL and IT participants, respectively. Among these, 45% and 35% (NL and IT) of REM cueing and 35% and 15% (NL and IT) of REM sham sessions resulted in at least one SVLD. In NL, the REM cueing sessions yielded 37 predefined eye signals with an average continuously verified lucidity duration of 78.75 ± 54.85 s. The REM sham sessions resulted in 15 eye signals in the presence of LD report (i.e, SVLD) and had an average duration of 47.80 ± 22.49 s. In IT, 48 predefined eye signals were identified within REM cueing sessions, with an average overall duration (i.e., from the first to the last predefined eye signal) of 506.33 ± 643.73 s and an average continuously verified (consecutive eye signals) duration of 91.13 ± 70.87 s. In contrast, 10 predefined eye signals were identified during REM sham sessions, with an average overall duration of 546.5 ± 744.58 s and a single continuously verified episode that lasted 20 s. Preliminary findings suggest that REM cueing aids the initiation and maintenance of lucidity, facilitates objective estimation of LD duration, and increases dream control. Future research should focus on automating the tools we provided and conducting larger-scale fully automatised studies at home to further explore factors contributing to such high success rates.

1. Introduction

Lucid dreaming (LD), the state of becoming consciously aware of being in a dream, is a captivating yet relatively rare phenomenon. While approximately half of the population has experienced spontaneous LD at least once in their lifetime, such occurrences remain quite infrequent (Saunders et al., 2016). Dream lucidity offers a distinctive opportunity for investigating the neuroscience of dreams by enabling the use of measurable lucidity verification techniques, such as predefined eye signals, breathing patterns, or facial muscle contractions (Laberge et al., 1981; Holzinger et al., 2006; Konkoly et al., 2021; Baird et al., 2022). This characteristic of LD offers improved experimental control over dream content and duration, enables external real-time monitoring, and even allows two-way communication with dreamers (Dresler et al., 2012, 2015; Siclari et al., 2017; Baird et al., 2019; Konkoly et al., 2021). Increasing levels of insight and control within dreams also holds promise for various clinical applications including treatment of nightmare disorder (Aurora et al., 2010; de Macêdo et al., 2019; Morgenthaler et al., 2018; Sandell et al., 2023; Spoormaker et al., 2006), nightmare-related symptoms in post-traumatic stress disorder (PTSD) (Holzinger et al., 2020; Yount et al., 2023) and narcolepsy (Rak et al., 2015), as well as for personal, recreational, and creative endeavours (Gott et al., 2020; Zink et al., 2013). Thus, a current challenge in dream research involves developing reliable methods to induce LD in everyday settings, clinical environments, and in the laboratory (Mota-Rolim et al., 2019; Adventure-Heart et al., 2020).

Previous efforts in LD induction encompass a wide range of approaches, including cognitive training (Appel et al., 2020; Adventure-Heart, 2020; Aspy et al., 2017; Baird et al., 2019; Dyck et al., 2017, 2018; Erlacher & Stumbrys, 2020; LaBerge et al., 2018; Saunders et al., 2017; Schredl et al., 2020; Taitz, 2011), external sensory stimulation during rapid eye movement (REM) sleep (Erlacher, Schmid, Bischof et al., 2020; Erlacher & Stumbrys, 2020; Kumar et al., 2018; Paul et al., 2014; Schmid & Erlacher, 2020), pharmacological interventions (Kern et al., 2017; LaBerge et al., 2018), brain stimulation (Blanchette-Carrière et al., 2020; Stumbrys et al., 2013; Voss et al. 2014), and combinations of different methods (Adventure-Heart, 2020; Carr et al., 2020; Erlacher, Schmid, Bischof, et al., 2020; Saunders et al., 2017; Erlacher, Schmid, Schuler, et al., 2020; Schmid & Erlacher, 2020). A comprehensive introduction to induction techniques can be found elsewhere (Stumbrys et al., 2012; Tan & Fan, 2023). While most approaches have shown little to moderate success rates at inducing objectively verified lucidity, targeted lucidity reactivation (TLR) has demonstrated the highest success rate in the laboratory to date (Carr et al., 2020). This induction method involves associating a pre-sleep lucidity training with sensory cues (visual and auditory) and then replaying the same cues during REM sleep. Such a procedure elicited lucid dreams in 50% of the participants, with objective lucidity

verification using a standard predefined eye movement pattern (looking left-right-left-right, LRLR) to signal lucid episodes within the dream. Another promising cognitive technique is the senses-initiated lucid dreaming (SSILD) method, which involves cycling through the different senses while falling asleep. This technique has garnered attention after being evaluated on a large sample of N=355 subjective reports (16.9% success rate), as it requires only a brief and easily implementable pre-sleep cognitive exercise (Adventure-Heart, 2020). However, validation of this technique with physiological recordings is still necessary (Tan & Fan, 2023).

The current body of research on LD induction techniques still presents significant limitations, including small sample sizes, reliance on self-reported questionnaires in absence of physiological data, and a predominant focus on individuals who already experience LDs frequently (≥ 1 lucid dream episode per month; Snyder & Gackenback, 1988), restricting the generalizability to the general population. To address these limitations, we designed a study that aimed to validate a novel combination of LD induction techniques with minimal methodological requirements in a large and heterogeneous sample of participants with variable prior LD experience. Our induction method combines SSILD-based cognitive training with multimodal (i.e., visual, auditory, and tactile) TLR in subsequent REM sleep periods using commercially available wearable devices. We compared the effects of SSILD training with and without further REM cueing during morning naps in the laboratory using a within-subject design, expecting that cueing during REM sleep would effectively increase dream awareness and control.

2. Methods

This multi-center study involved data collection in three sleep laboratories located in the Netherlands (NL)[1], Canada (CA)[2], and Italy (IT)[3]. The experimental protocol was preregistered[4] prior to data collection in participating centers (Esfahani, Salvesen, Picard-Deland, et al., 2022) and is presented here with some minor textual modifications to enhance clarity. In order to obtain a pooled sample of N = 60, each center recruited 20 participants who completed two nap sessions with at least one REM episode each, following a within-subject design. We employed minimal sensing systems, i.e., an EEG wearable headband (ZMax, Hypnodyne Corp., Sofia, Bulgaria) with three additional chin electromyography (EMG) electrodes, and our dream engineering toolbox (Dreamento[5]; Esfahani, Daraie et al., 2023).

2.1. Participants

We aimed to recruit a total of 60 participants (20 per center; NL, CA, IT) who completed two experimental morning nap sessions with REM sleep. Participants were recruited through flyers, word of mouth, and online recruitment strategies specific to each research center (e.g., SONA system[6] for the NL site, social media). The compensation for the entire study was 70 EUR in European centers and 120 CAD in Canada. Interested participants were first screened for general inclusion and exclusion criteria (see Supplementary Table 1). Inclusion criteria included being healthy, aged between 18 and 55, having a regular sleep-wake pattern, at least one prior lucid dreaming experience, and frequent dream recall of at least three times per week. Exclusion criteria included presenting history of neurological, psychiatric, or neurodegenerative disorders, prior brain surgery, epilepsy diagnosis, pregnancy, and the use of sleep-altering medication.

Participants completed a series of questionnaires and were further screened for depression (Beck Depression Inventory (BDI-II), score ≥ 20), anxiety (Beck Anxiety Inventory, score > 15), prodromal symptoms (Prodromal Questionnaire 16-item version, score ≥ 9), sleep quality (Pittsburgh Sleep Quality Index, score > 7) and chronotype (Morningness Eveningness Questionnaire, Sleep time before 23:00 or Rise time before 07:00). Additional questionnaires collected information on their

[1] Donders Institute for Brain, Cognition and Behaviour, Radboud University Medical Centre, Nijmegen, The Netherlands

[2] Centre for Advanced Research in Sleep Medicine, Hôpital du Sacré-Coeur de Montréal, Montreal, Quebec, Canada

[3] Sleep, plasticity, and conscious experience group, MoMiLab Research Unit, IMT School for Advanced Studies Lucca, Lucca, Italy

[4] https://osf.io/u5m3z

[5] https://github.com/dreamento/dreamento

[6] https://radboud.sona-systems.com/

sleep, dreams and waking cognition: Mannheim Dream Questionnaire (MADRE) and Vividness of Visual Imagery Questionnaire (VVIQ; see also Supplementary Table 1-3).

2.2. Study procedure

The study timeline is described in Figure 1. After an online or short phone screening process, eligible participants were invited to the intake session (in person at NL and IT sites, online at CA site), during which they received detailed information about the study and provided informed written consent. They then came twice in the laboratory for two morning nap sessions, held approximately one and two weeks after the intake session. They were asked to keep a home dream diary starting approximately 1 week before the first nap up until the second nap (total of ~2 weeks). Both nap sessions involved a SSILD cognitive training procedure associated with a set of sensory cues during wakefulness. One of the sessions also included cueing during subsequent REM sleep periods (REM cueing), while the other did not (REM sham; order counterbalanced across participants). Participants were asked to signal lucidity or cue perception in real-time using a predefined eye movement pattern (left-right-left-right, LRLR) and to report any subjective experiences upon awakening. In order to assess any eventual long-term effects of our induction technique on dreams, an optional 'exit questionnaire' was sent 2 weeks after the last experimental session to ask for any changes in the lucid dream frequency of our participants.

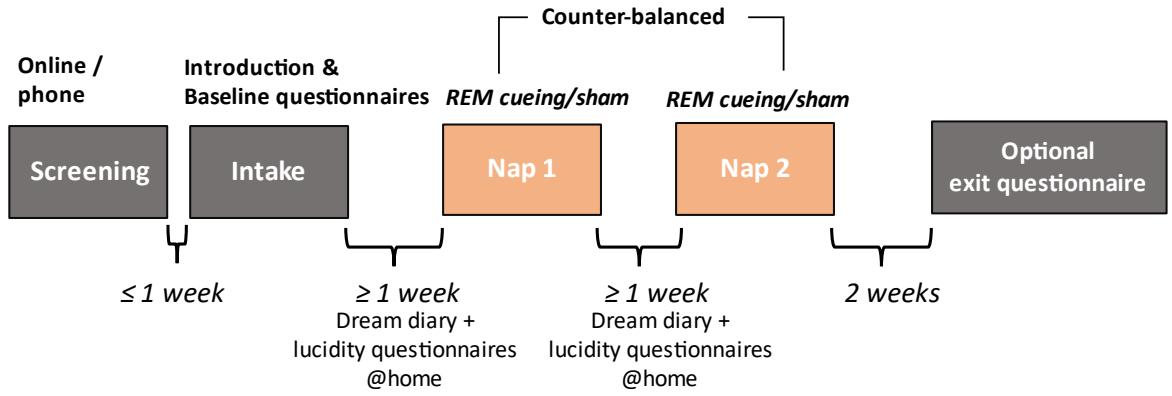

Figure 1 - General timeline of the study procedure.

In this study, a nap "trial" denotes each sleep opportunity within an experimental nap session (see section 2.3). A nap trial is deemed valid if it involves correctly identified REM sleep and the appropriate stimulation procedure (either cued or sham, depending on the session condition). We considered a participant valid if they achieved at least one valid nap trial in both experimental nap sessions. Thus, if a participant failed to reach REM during a single session, a replacement participant

was recruited to reach the targeted final sample. All analyses in this paper are based on valid participants. Participants were told that both naps may or may not be cued in order to remain blind to the experimental condition.

2.2.1 Sleep and dream diaries

Participants were required to document their sleep-wake schedule and subjective assessment of sleep quality for the entire duration of the study. Dream reports and a Dream Lucidity Questionnaire (DLQ; Stumbrys et al., 2013) were also collected daily (not analysed here). Home diaries were accessed online via Castor EDC[7], an electronic data management platform (NL and IT centers), and using REDCap software in the CA center.

2.3. Experimental nap protocol

Participants arrived at the lab at 07:00 a.m. in NL and CA sites and between 05:00 - 08:00 a.m. in IT, depending on participants' usual sleep-wake schedule and laboratory availability. They were requested to refrain from consuming any alcoholic or caffeinated beverages (e.g., coffee or tea) in the evening and morning before the nap sessions.

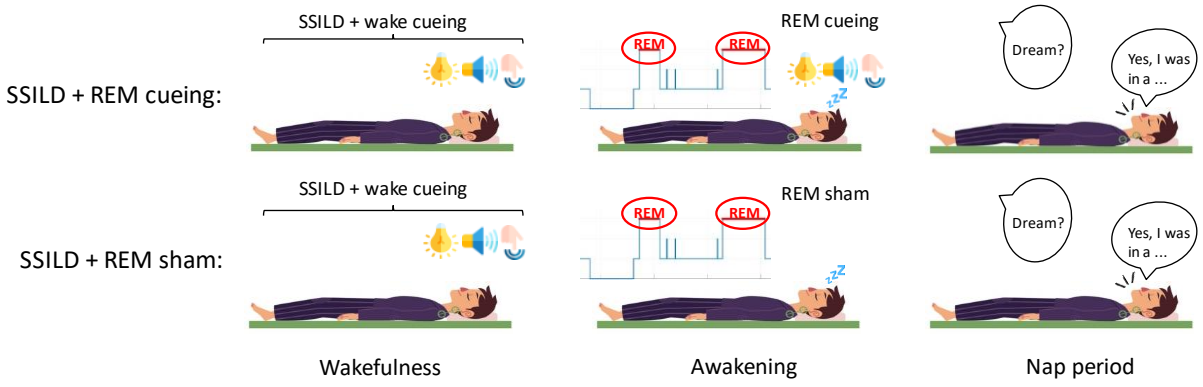

Figure 2 - Schematic representation of the protocol during the experimental nap sessions.

The experimental protocol for the nap sessions (Figure 2) was based on a modified version of the SSILD procedure. Both sessions followed the same structure during the wakefulness period preceding sleep, which comprised almost 30 minutes of cognitive training with sensory stimulation (see section 2.3.2). Once the cognitive training concluded, participants were allowed to sleep for up

[7] https://www.castoredc.com/

to 2.5 hours. The experimental procedure for each nap session (Figure 2) followed our preregistered study protocol[8].

2.3.1. Cognitive training

The cognitive training was based on a vocal recording which lasted for approximately 30 minutes and was divided into different blocks (Figure 3; Supplementary Material 1 and Supplementary Table 4). After a short introduction, participants were guided through a series of SSILD cycles, during which they were instructed to lie with their eyes closed and focus their attention towards each sensory modality (i.,e, vision, hearing, touch), starting with fast (2-3 s), followed by medium (20 s), and ending with slower (60 s) cycles. During slow cycles, each sensory step was associated with the corresponding cue (i.e., light, sound, vibration): the cue indicated the end of a sensory step and the initiation of the next one. A vocal prompt reminding the participant to practice a lucid mindset accompanied the cues during the first half of the slow cycles; cues were then presented alone and the participant could fall asleep normally.

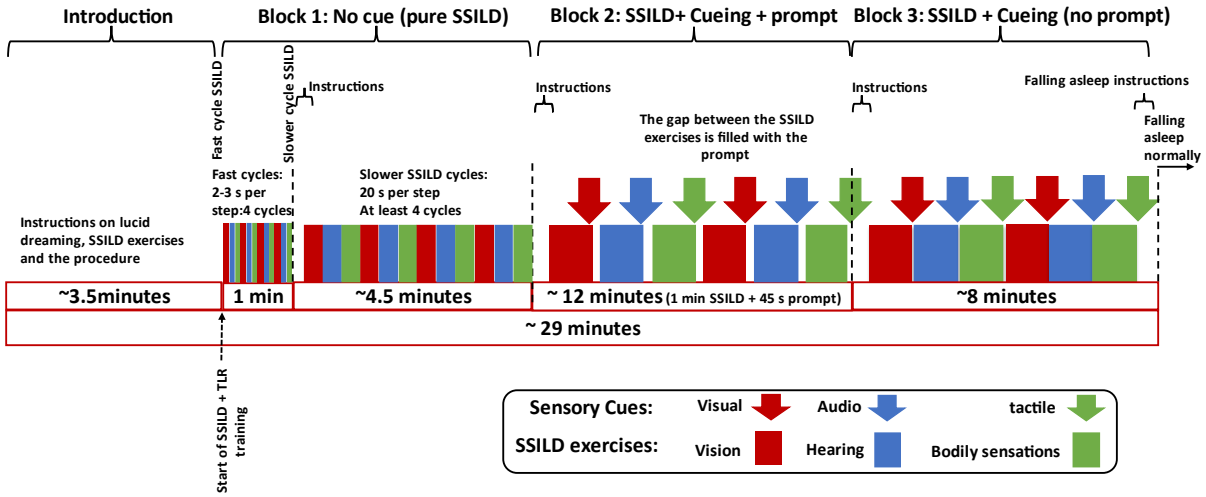

Figure 3 - Structure and timing of the cognitive training protocol. *Block 1: SSILD exercises without stimulation (fast and slower cycles). Block 2: A combination of the SSILD exercises with associated multimodal sensory stimulation (i.e., visual, audio, tactile) with verbal prompts. Block 3: A combination of the SSILD exercises with associated and multimodal sensory stimulation (i.e., visual, audio, tactile) without verbal prompts. N.B: while overall length was highly similar for all centers, the timings above correspond to the English recording, and slight block timing variations were possible due to language differences.*

[8] https://osf.io/u5m3z

Before proceeding with the cognitive training, the baseline intensity thresholds for visual ('**minimum subjective light intensity**') and auditory stimuli ('**minimum subjective audio volume**'), as well as the continuous background noise level, were individually adjusted based on the subjective appraisal of the participant (for more details, see Supplementary Materials 2).

2.3.2. REM cueing protocol

Cueing during sleep started about 20 seconds after detecting the first rapid eye movement in the context of low EMG activity, indicating the initiation of phasic REM sleep. The sensory cues were played in the same cyclic order as in the cognitive training cycles during wakefulness (i.e., visual, auditory, and tactile) approximately every 20 seconds.

The experimenter started the cue presentation from the previously assessed lowest subjective *perceptual* thresholds (see *Section 2.3.1*). The intensity of each cue was gradually increased for as long as REM sleep continued without any sign of arousal. Audio and visual cues were increased by 5 dBA and 5% in each cycle, respectively; vibration cues were increased from one repetition up to three repetitions in subsequent cycles.

If the participant reacted to a cue with intentional predefined eye signaling (LRLR), intensity levels were left unchanged until awakening. Whenever signs of microarousal were detected (e.g., a relative increase in EMG activity or in alpha activity), stimulation was temporarily halted and resumed only after the complete dissipation of such signs. Thereafter, cueing was continued by decreasing the intensities to the step previous to the arousal-provoking cycle (i.e., decreasing 5% light, decreasing 5 dBA from the audio cue, and adjusting the tactile cue accordingly), followed by the previously described gradual intensity increments. At the end of each nap trial, intensity levels for all cues were reset to their corresponding baseline cue intensity.

2.3.3. Dream interview

Participants were woken up at the end of each REM period to report any subjective experience they could remember from the last moments before waking up, including any sensations, feelings, thoughts or emotions (Figure 4). Participants were also asked if they were feeling asleep during this time and if they were aware of their conscious state; whenever possible, further details about the experience were collected (i.e., estimated length, precise content, cue perception, presence of eye signaling, following the dialogic structure Supplementary Material 4).

To increase the likelihood of participants falling asleep repeatedly during the allocated 2.5h time-window, the experimenter attempted to keep the intermediate nap trial awakenings' interview brief, especially when no significant experience was reported. After the semi-structured interview was completed, participants were asked to answer the DLQ based on the reported experience, except when no subjective experience was reported (i.e., reporting having had no conscious experience or a conscious experience without recall).

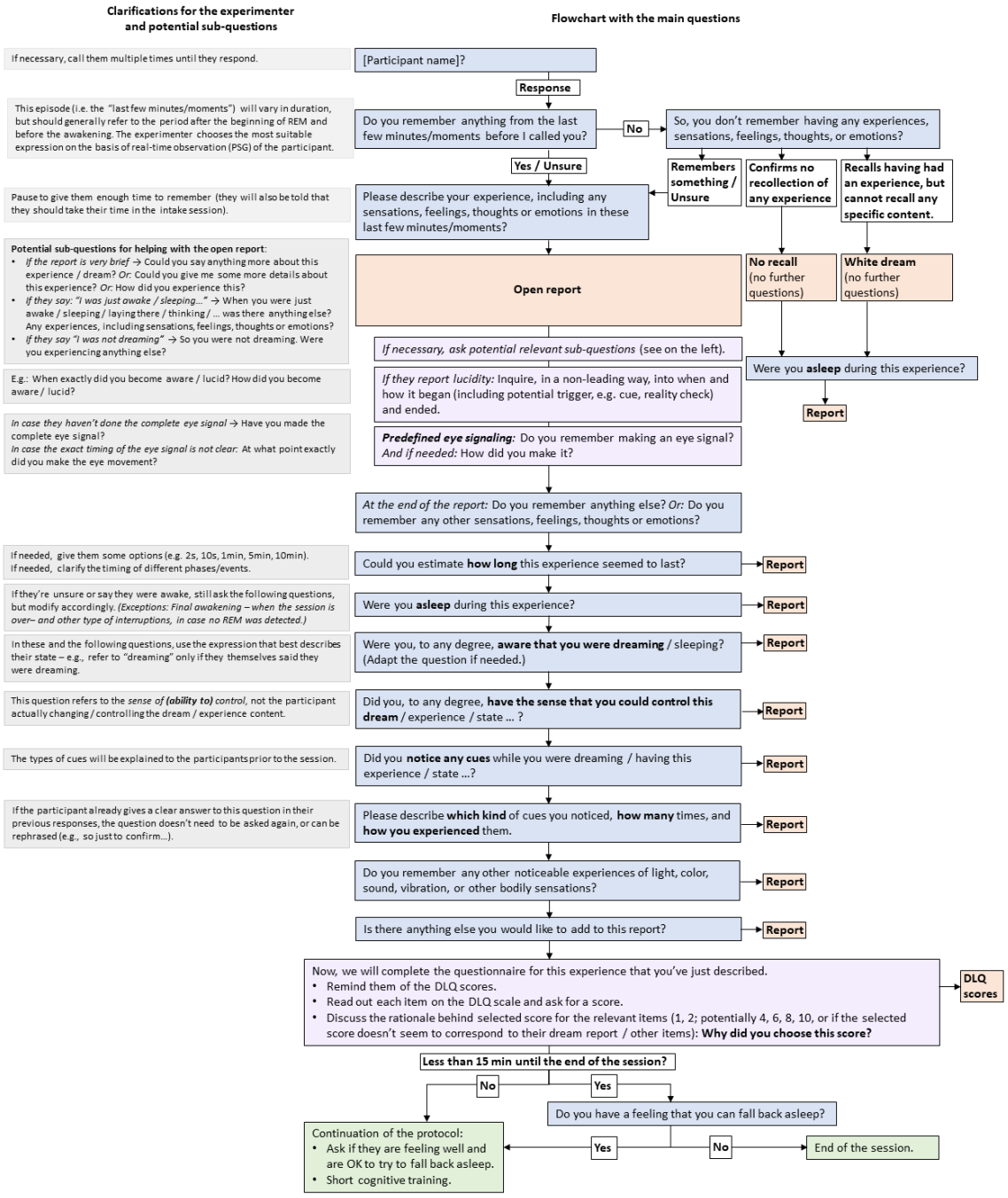

Figure 4 - Flowchart of the semi-structured dream report interview following each experimental awakenings

After completing the dream interview, an additional nap trial was attempted until the 2.5 h were completed. Each time, participants listened to a short version of the SSILD training consisting of a few minutes of uncued fast and slow cycles, followed by a single cued SSILD cycle without verbal prompts, after which participants could fall back asleep.

Dream reports were also collected at the end of the nap session (after 2.5 hrs had elapsed), upon a spontaneous LD report from the participant, upon observing a LRLR signal during non-REM sleep, or upon experimental interruptions. Upon final awakening, the participant was asked to complete the LuCiD scale questionnaire (Voss et al., 2013) for every reported subjective experience.

When more than one REM trial with questionnaires (i.e., DLQ, LuCiD) was collected during a single nap session, the measures were averaged within the session. Therefore, the mean value for all trials within the session was used for further statistical comparison between conditions.

2.3.4. Lucid dream task

Participants were asked to do an intentional predefined eye movement sequence (i.e., LRLR) in the following cases: (1) whenever they became aware of the fact they were dreaming, allowing for an objective marker of the "initiation" of the lucid episode; (2) each time a cue was perceived during sleep, providing a physiological marker for potential dream incorporations of the stimuli; (3) approximately every 30 seconds if no sensory cue was perceived, to estimate the duration of the lucid dream. This approach was aimed at providing a more objective measure of the initiation and duration of each lucid dreaming episode.

Participants were also informed about the high probability of dreaming about the sleep laboratory and experiencing a false awakening. They were instructed to react to such an event by engaging in a reality check, using techniques like attempting to breathe through a pinched nose or counting their fingers, whenever they encountered uncertainty regarding their waking or dreaming state. Furthermore, if the participants entered a state of dream lucidity, they were advised to engage in exploration or observation of the dream scene and avoid performing exciting actions, such as flying or free-falling during the first few seconds of lucidity to maximize the chances of maintaining lucidity for a longer duration.

2.4. Signal acquisition

Electroencephalographic measurements were collected using ZMax EEG headbands (Hypnodyne Corp., Sofia, Bulgaria), a validated sleep wearable device (Esfahani, Weber et al., 2023) equipped with various sensors, including two frontal EEG channels (F7-Fpz, F8-Fpz), an accelerometer, a Photoplethysmography (PPG) sensor, ambient light and sound sensors, and a thermometer. Simultaneously, three electromyographic (EMG) channels recorded muscular activity from the chin area (see *the preregistration of the study for exact locations)* using laboratory-specific systems (NL: BrainAmp ExG, Brainproducts GmbH, Gilching, Germany; IT: g.USBamp Research, g.tec medical engineering GmbH, Graz, Austria; CA: Natus Embla® NDx Amplifier, Middleton, USA) through system-specific software (NL: BrainVision; IT: g.Recorder for g.tec Suite; CA: Natus SleepWorks). In the CA site only, an additional standard polysomnography (PSG) montage was applied (EEG: F3, F4, C3, C4, O1, O2; 2 horizontal EOG channels).

We relied on the open-source dream engineering toolbox Dreamento (Esfahani, Daraie et al., 2023) for real-time EEG signal monitoring, recording, sensory stimulation, and offline data analysis. For redundancy, the ZMax signals were also recorded through the manufacturer's proprietary software, as suggested in (Esfahani, Daraie et al., 2023). Once the individual stimulation thresholds were determined during the experimental nap sessions, a calibration period started, consisting of one minute of closed-eye resting wakefulness, which provided the baseline reference for restful physiological measures. Participants were also asked to clench their teeth three times in a row in order to synchronize the electromyographic (EMG) recordings with the headband recordings at the beginning and end of the recording, as well as after any awakening or experimental interruption (Supplementary Material 2, and Supplementary Table 5). The EEG and EMG signals were then synchronized using designated functions in Dreamento. The participants were also instructed to perform the lucidity signal (predefined LRLR eye movement) while keeping their eyes closed, in order to serve as a blueprint for identifying individual LRLR signals during subsequent sleep. At the end of the calibration period, cognitive training was started.

2.5. Sleep scoring

The data collected from each site underwent sleep scoring by researchers from the other two sites. Manual scoring was performed using Offline Dreamento, and included scoring of sleep stages, arousals, and predefined eye signals. The raters were blind to the condition and real-time annotations (Supplementary Table 6) and did not have access to the corresponding subjective data (e.g., dream reports, questionnaires).

Inter-rater agreements (Supplementary Table 10) for the scoring of each nap was computed using Cohen's kappa statistic. Since the lack of occipital EEG channels occasionally challenged the differentiation between Wake and N1, particularly when frontal alpha activity was not apparent, we opted to merge Wake and N1 sleep stages for computing inter-rater agreements. If the agreement score of a nap session fell below the 80% threshold, the scorers would reevaluate the epochs with conflicting stages until they reached a consensus. Sleep assessment metrics were evaluated using a dedicated Python toolbox (YASA; Vallat & Walker, 2021).

2.6. Lucid dream classification

In this study, a signal-verified lucid dream (SVLD) was confirmed in the presence of both objective and subjective measures of lucidity, i.e., when 1) a predefined eye movement (LRLR) was detected *and* 2) the subject reported becoming lucid and performing the signal.

A lucid dream was considered non-signal verified (non-SV LD) whenever the participant reported becoming lucid and/or indicated being at least *'moderately'* aware of being in a dream (based on the first question of the DLQ, "*I was aware that I was dreaming*") in *absence* of any reported predefined eye signaling, whether or not it was detected by the scorers. Additionally, we classified non-lucid dreams that were associated with detected predefined eye signal in the absence of dream awareness as "signaled non-LD". Dreams were considered "non-LD" when subjects did not report awareness while dreaming and no predefined eye signal was detected during the REM sleep period preceding the awakening.

Predefined eye movements were scored by all three main experimenters (MJE, LS, and CPD). Only signals that were identified by at least 2 out of 3 scorers were considered. The duration of SVLD was determined in two ways: 1) from the first to the last predefined eye signal within the same REM period (i.e., overall SVLD duration) and 2) by only considering the time between consecutive eye signals occurring within one minute after each other (i.e., continuous SVLD duration). This threshold was chosen because in cases where participants perceived only a single type of cue (as observed in some instances), the same cue type was presented every minute (considering the predefined 20 s interval for playing visual, auditory and tactile cues).

If the participant performed an intentional lucidity signal *different* from the predefined LRLR eye movement (e.g., partial, such as LRL, or slower than the baseline LRLR eye movement performed

during wake), it was accepted as a lucidity signal only if the participant reported attempting to perform the predefined lucidity signal. Average scores of DLQ and LuCiD were also used to assess the *level* of lucid scale factors such as *insight, control, thought, realism, memory, dissociation, negative emotion*, and *positive emotion (*Voss et al., 2013).

2.7. Statistical and methodological evaluation

Statistical analyses were performed using Python and R. Plots and figures were created using dedicated Python *'matplotlib'* (Hunter, 2007) and R packages *'ggplot2'* (Wickham, 2016) and *'raincloudplot'* (Allen et al., 2021). To summarize our findings, we employed descriptive statistics. Mean (M) and standard deviation (SD) were computed for all measurements. Additionally, for data that did not exhibit a normal distribution, median (MED) and interquartile range (IQR) were provided. Statistical testing on continuous data was performed using paired t-tests or Wilcoxon signed-rank tests, depending on whether the data normality assumptions were met (Shapiro–Wilk test and D'Agostino-Pearson tests). McNemar tests were used to compare paired nominal data, such as the presence or absence of (SV)LD as a function of the experimental condition. Friedman tests were used to compare eye signal response times as a function of the 3 different cue modalities. Of note, statistical tests comparing lucidity-related measures between both experimental conditions were one-tailed, following our hypothesis that measures from REM cueing sessions would be higher than REM sham sessions. Tests comparing sleep assessment metrics were 2-tailed, since we did not expect any particular differences between conditions.

The methodological quality of the present study was evaluated by an independent rater using the adapted Downs & Black (1998) methodological assessment checklist (Salvesen et al., 2024). This 23-item checklist examines a series of aspects concerning internal and external validity, as well as the reporting of the methods and outcomes, providing a score ranging from 0 to 25. This allows for an objective and comparable measure of scientific rigor, as exemplified in previous (lucid) dreaming literature (see systematic reviews in Stumbrys et al., 2012; Tan & Fan, 2022; Salvesen et al., 2024), with the adapted version having been designed to optimally serve the evaluation of sleep and dream engineering studies.

3. Results

The results section of this preprint comprises the findings from the NL and IT study sites, which are presented separately. Once the data collection and analysis at the CA center are completed, the results will be merged and reported for the final publication. The methodological score for this study

is 20 out of 25 (see section 2.7 and Supplementary Table 9 for a detailed account of all checklist items). This score is a compound of the assessment of several aspects of the present manuscript: reporting (10/10), external validity (2/4), internal validity - comprising bias (6/7) and confounding (2/2), and power (0/2; note, merging data from all study sites will allow for power calculations).

3.1. NL study site

3.1.1. Participants

We enrolled 35 participants in the NL site, of which 5 were excluded due to their baseline questionnaire responses (4 according to BAI, 1 according to PQ-16), 9 managed to reach REM in only one session (1 quit after the first nap), and one participant failed to enter REM in either session. The remaining 20 valid participants (14 females, aged 23.3 ± 3.95 years) reliably achieved REM in both nap sessions (Figure 5).

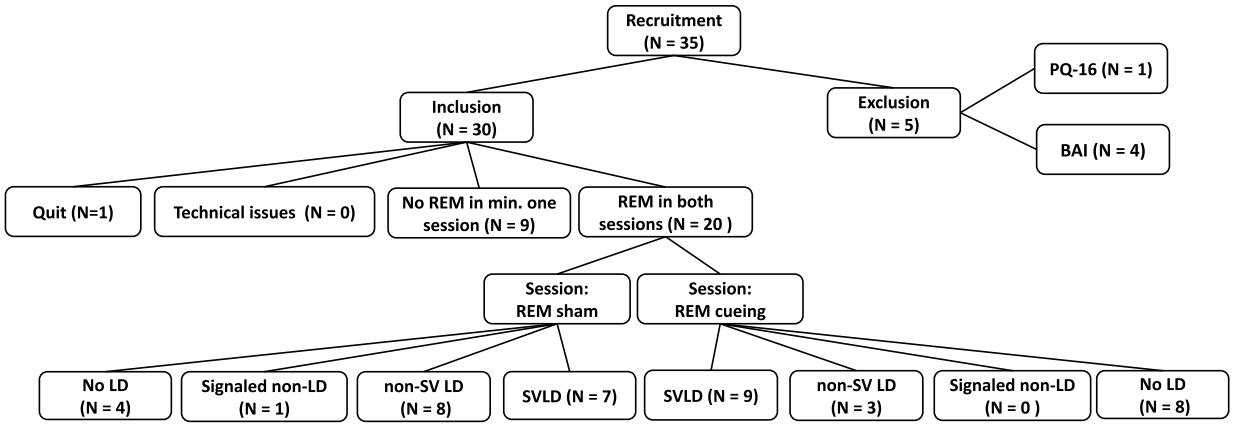

Figure 5 - Participant counts categorized by signal-verified lucid dreams (SVLD), non-SV LD, and signaled non-LD. *SVLD denotes the subjective reporting of LD alongside predefined eye signal confirmation. Non-SV LD refers to subjective LD reports without signal verification, while signaled non-LD indicates the identification of predefined eye signals without concurrent subjective lucid dreaming reports. See also Supplementary Table 7.*

3.1.2. Sleep measures

Following the initial independent sleep scoring by the scorers from other study sites, we reached a Kappa score of 0.82 ± 0.12 and 0.69 ± 0.12 with and without combining W and N1 stages, respectively (Supplementary Table 7). The W-N1 combined scorings with < 80% Kappa were then adjusted as described in the methods (section 2.5). Notably, with the exception of the latency of N2 sleep, none of the sleep assessment metrics (e.g., sleep efficiency or any of the REM-related measures) showed significant differences between conditions, indicating that cueing during REM did not affect

overall sleep quality (Supplementary Table 6). The latency of N2 sleep was shorter in the REM sham condition (34.75 ± 13.35 m) compared to REM cueing (49.8 ± 30.57 m, p = 0.001).

3.1.3. Lucidity measures

Seventeen of 20 (85%) participants experienced at least one lucidity episode, whether objective or subjective, during the study. Thirteen out of 20 (65%) experienced at least one SVLD trial, and the remaining 4/20 (20%) subjectively reported lucid dreams in the absence of signal verification. From the remaining 3/20 (15%) participants who did not experience a LD in the lab, in one instance, the predefined eye signals were identified in the lack of LD report (signaled non-LD) and the other two were non-LD cases. Figure 5 shows the summary of the participants' inclusion and the resulting sessions. Table 1 represents the distribution of SVLD, non-SV LD, and signaled non-LD experiences in relation to the prior lucidity experience of the valid participants.

Prior LD frequency (LDF).		**2 SVLD sessions**	**1 SVLD session**	**1 non-SV LD session**	**2 non-SV LD session**	**1 Signaled non-LD session**
Never	0	NA	NA	NA	NA	NA
Less than once a year	5	0	2	2	0	0
About once a year	2	0	1	0	0	1
About 2-4 times a year	7	2	3	3	1	0
About once a month	4	0	3	1	1	0
2-3 times a month	0	NA	NA	NA	0	NA
About once a week	2	1	1	1	0	0
Several times a week	0	NA	NA	NA	0	NA
Total	20	**3**	**10**	**7**	**2**	**1**

Table 1. Counts of participants with SVLD, and non-SV LD and signaled non-LD at the lab based on estimated LD frequency before the study.

Overall, we identified at least one SVLD in 16/40 (40%) of sessions, 9/16 (56%) of which occurred during the REM cueing sessions, and 7/16 (44%) SVLDs during the REM sham sessions. In other words, while 9/20 (45%) of REM cueing sessions yielded SVLD, 7/20 (35%) of REM sham sessions resulted in SVLD. Nevertheless, no significant difference was found in terms of the presence of at least one SVLD between conditions (McNemar test, χ^2 (1) = 0.4, p = 0.26). Notably, while we did not detect more than one SVLD trial across different trials of a single REM sham session, we identified SVLD in two distinct trials of two REM cueing sessions (Figure 6). In total, we identified 82 valid REM trials: 45 REM sham and 37 REM cueing, out of which, 18 (40.00 %) and 15 (40.54%) contained lucid experiences, respectively. Among these lucid experiences, 7 out of 18 (38.89%) resulted in SVLD in the sham condition, compared with 11 out of 15 (73.33%) in the cueing condition. This suggests that REM cueing led to a higher signal-verification rate compared to REM sham, although the difference was not statistically significant..

In all participants, a total of 58 predefined eye signals were identified, among which 13 were in response to visual cues, 13 to auditory cues and 11 to tactile cues (within the same epoch). Among the 19 spontaneous eye signals, 17 were during REM sham sessions (15 being SVLDs), and the other 2 were during REM cueing sessions; however, not in the vicinity of any sensory cue (i.e., spontaneous eye signals). Comparing REM cueing to REM sham conditions, our examination revealed a nearly significant uptick in the number of predefined eye signals within REM cueing sessions (39 vs. 15, Wilcoxon rank sum exact test, W=44.5, p = 0.08). The response time to the sensory cues were relatively short: 3.12 ± 2.75 s on average (visual: 3.36 ± 2.62 s, auditory: 3.87 ± 3.54 s, tactile: 1.96 ± 0.67 s).

Overall SLVD duration (see Section 2.6) was 162.15 ± 137.98 s. Average SVLD duration was longer in REM cueing trials (211.13 ± 140.34 s, ranging from 45 to 473 s) than inREM sham trials (83.80 ± 89.49 s, ranging from 15 to 260 s) (Wilcoxon rank sum exact test, W=32, p = 0.046). The estimated continuous SVLD duration (on average: 66.85 ± 45.18 s) also tended to be longer in REM cueing session (78.75 s ± 51.31 s) when compared with in REM sham sessions (47.80 s ± 22.49 s; Wilcoxon rank sum exact test, W=28, p = 0.14).

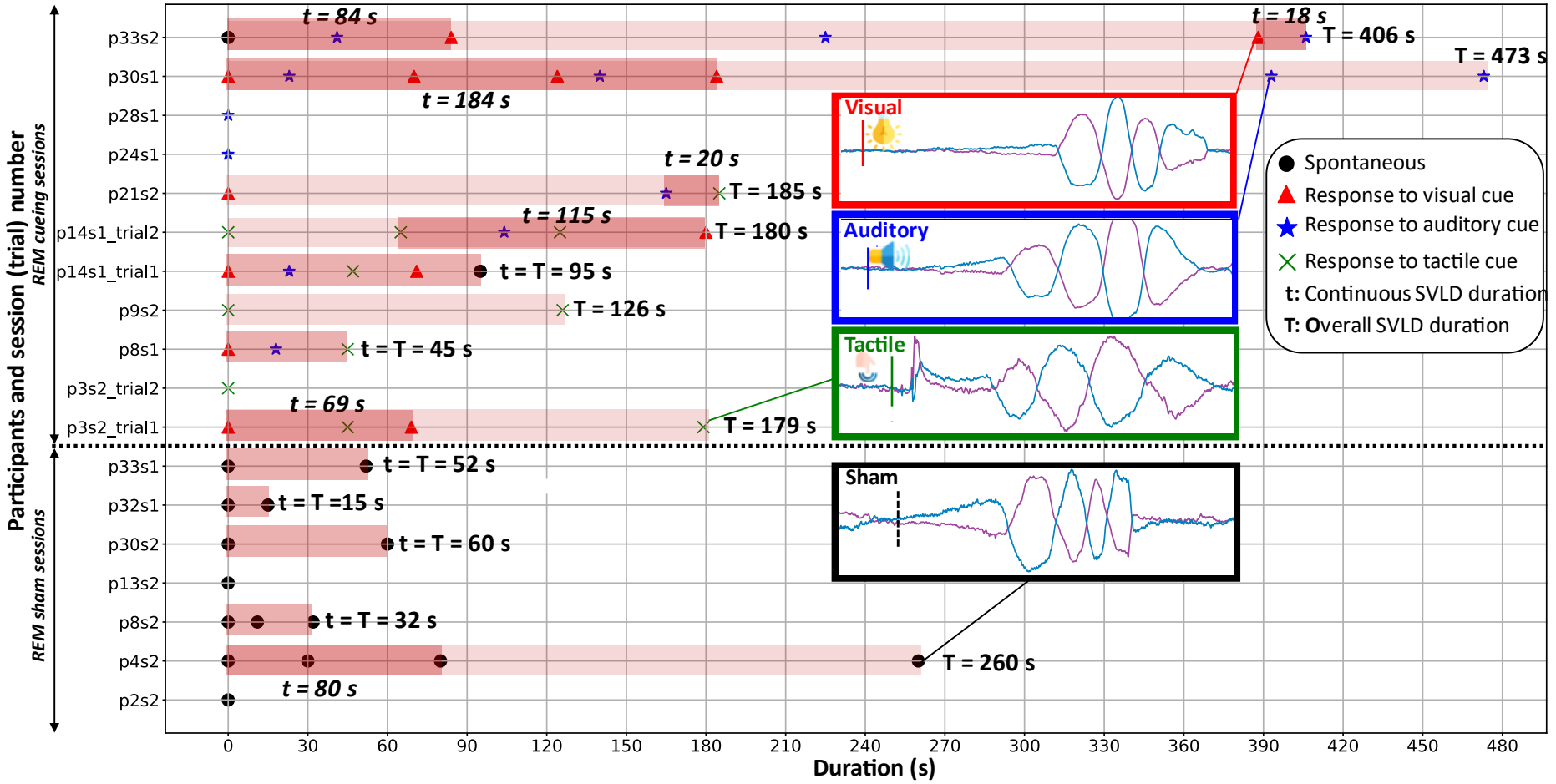

Figure 6 - Visualization of signal-verified lucid dreams (SVLDs) and their estimated duration per participant at the NL study site. *Below the horizontal line, SVLD occurrences during "REM sham" sessions are depicted, while those during "REM cueing" sessions are displayed above the line. Continuous (dark red; t: continuously verified time in seconds) and overall (light red; T: overall verified time in seconds) SVLD duration are highlighted. The initial verified eye signal within each trial was time-locked to t=0, and subsequent eye signals (if any) were plotted sequentially to estimate the duration of continuous SVLD duration (highlighted in red). The overall SVLD duration is equal to the timestamp*

of the last eye signal within each trial. Spontaneous eye signals occurring during REM sham sessions (without cues) or during REM stimulation sessions outside the context of sensory cues (e.g., before stimulation or during stimulation pauses due to potential signs of micro arousal) were shown with black circles. Responses to sensory cues were marked in red for visual cues, blue for auditory cues, and green for tactile cues.

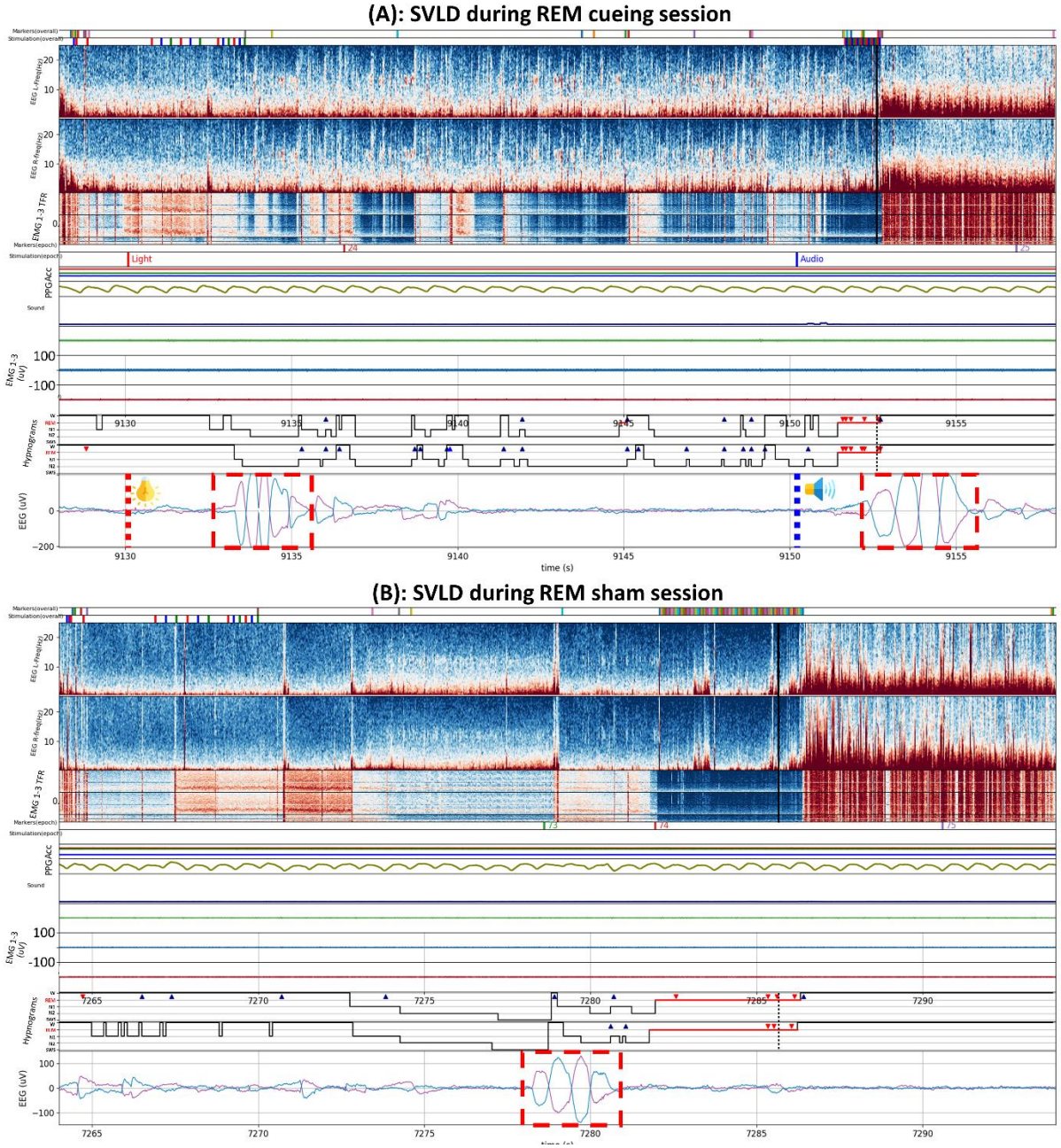

Figure 7 - Sample SVLD cases during (A) REM cueing and (B) REM sham sessions from Dreamento user interface. *An accurate interpretation of each subplot can be found in Dreamento publication (Esfahani, Daraie et al., 2023). (A) two subsequent predefined eye signals after the presentation of visual and auditory cues. (B) Spontaneous predefined eye signal. In both cases, two independent raters scored the epoch as REM sleep and agreed on scoring the eye signal as a predefined LRLR lucidity signal. The hypnograms feature dark triangles indicating arousal markers and red triangles denoting the detection of predefined eye signals. The vertical dashed*

line on the hypnogram represents where the current epoch of data is located with respect to the scoring. The predefined eye signals were marked using red rectangles in the EEG signal.

In 10/40 (25%) of the sessions, there was a non-SV LD experience based on reports only, and during a single session (2.5%), a participant reported LD but not performing eye signals, whereas the consensus of scorers identified predefined eye signals in the EEG, making it another instance of non-SV LD. Among these non-SV LD cases, 73% occurred during REM sham sessions, and only 23% took place during REM cueing sessions. In 1/40 (2.5%), the consensus of scorers agreed on identifying a predefined eye signaling; however, the participant did not report lucidity (signaled non-LD). These both happened during REM sham sessions. In the remaining 12/40 (30%) of the sessions there was no LD experience, either signaled or not.

When comparing the average DLQ scores between sessions, there were no significant differences observed. This included the first question concerning awareness while dreaming (REM sham: 1.61 ± 1.27, REM cueing: 1.36 ± 1.39, t-test, t=60, p=0.72), as well as the fourth question related to the dreamer's ability to control their actions (REM sham: 1.59 ± 1.54, REM cueing: 1.65 ± 1.61, Wilcoxon signed-rank test, W=93.0, p=0.48), and the overall total score (REM sham: 7.88 ± 5.77, REM cueing: 9.65 ± 9.69, Wilcoxon signed-rank test, W=91.5, p=0.44) (see also Figure 8). We also did not find any notable variances across all LuCiD factors between conditions. However, in terms of the memory factor, there was a tendency towards higher levels in REM cueing compared to REM sham (t-test, t = -1.62, p = 0.06; see Figure 9).

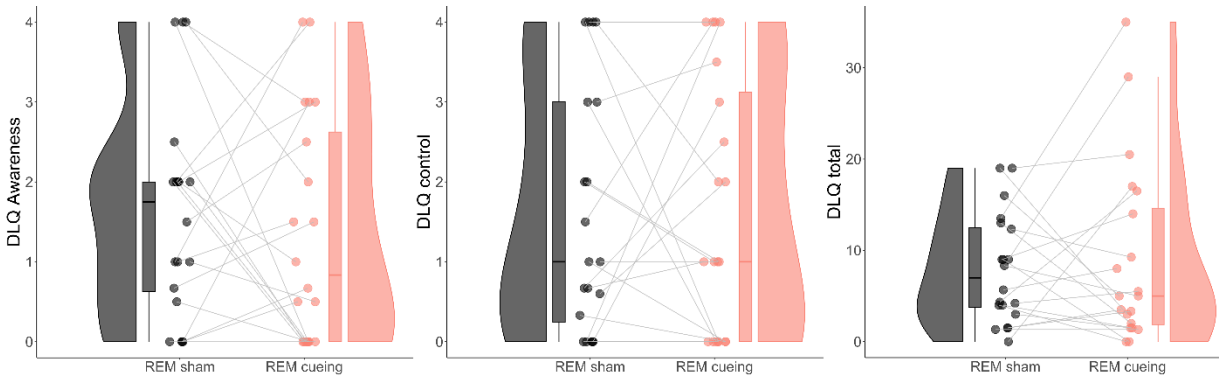

Figure 8 - Between-session DLQ scores comparison. *No significant difference was found in terms of the DLQ first, fourth, and total score.*

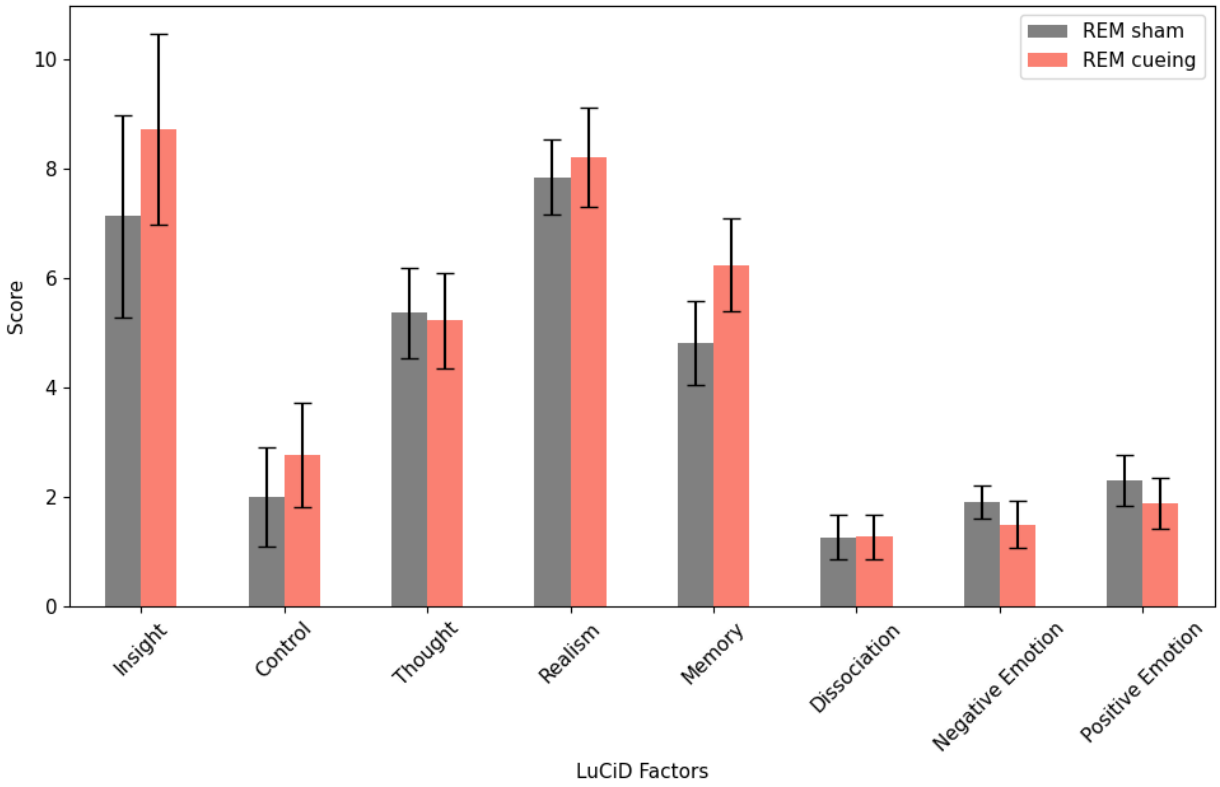

Figure 9 - LuCiD scores comparison. (A) *comparing all the REM cueing vs REM sham sessions. Insight: t = 74.0, p = 0.13, control: t = 73.0, p = 0.24, thought: t = 0.15, p = 0.56, realism: t = -0.43, p = 0.34, memory: -1.62, p = 0.06, dissociation: t = 102.0, p = .53, neg_emotion: t = 115.0, p = 0.75, pos_emotion: t = 130.5, p = 0.83.*

3.2. IT study site

3.2.1 Participants

Overall, 57 participants were recruited at the IT site. Of them, 14 were excluded after the intake session due to above-threshold scores according to at least one baseline questionnaire: 5 according to PQ-16, 1 according to BAI, and 8 according to more than one questionnaire. Furthermore, 4 participants dropped out voluntarily after the intake session. Among the remaining participants, 13 did not enter REM sleep in at least one experimental nap session (of which 1 dropped out voluntarily after the first experimental nap session). We encountered technical difficulties involving signal loss or high noise levels on 6 occasions, rendering the sessions unscorable, thus invalidating the participants. Our final sample consisted of 20 valid participants (age: 30.75 ± 6.84; 11 males) upon which all further analyses are based (see Figure 10).

3.2.2. Sleep measures

Following a first round of independent sleep scoring of all nap sessions by the experimenters from the other two study sites, Cohen's Kappa scores reached substantial to nearly perfect agreement, depending on whether W and N1 stages were combined (0.83 ± 0.11) or not (0.67 ± 0.13). Based on the Kappa metrics after combining W and N1, nap sessions for which the sleep scoring did not attain the 80% agreement threshold (13/40) were re-evaluated by both scorers until reaching a consensus (see Section 2.5 for further details).

Standard measures of sleep showed that the REM cueing procedure did not affect global sleep architecture and efficiency (see Supplementary Table 10). Only two metrics differed between REM cueing and REM sham naps: sleep period time (SPT) was significantly higher for REM cueing (164.03 ± 16.13 min) compared to REM sham (151.65 ± 16.20 min; Wilcoxon sign-rank test, $W = 32$, $p = 0.005$), while the percentage of N2 sleep relative to total sleep time was significantly lower for REM cueing (46.49 ± 11.78 min) than for REM sham (54.95 ± 14.51 min; paired T-test, $t = 2.48$, $p = 0.02$).

3.2.3. Lucidity measures

Out of our 20 valid participants, 12 (60%) experienced at least one lucidity episode throughout the study, of which 9 (75%) were signal-verified. When evaluating lucidity rates as a function of the experimental condition, we observed that 9 (45%) participants achieved lucidity during the REM cueing sessions, out of which 7 (77.78%) also signaled it (SVLD). Concerning the REM sham sessions, 9 (45%) participants attained lucidity, but only 3 (33.33%) achieved SVLD. The presence of SVLD was

significantly different between experimental conditions, with more SVLD in REM cueing than in sham sessions (McNemar test, χ^2 (1) = 3.0, p = 0.021). Importantly, we were able to induce lucidity, both signaled and not, in participants who did not previously identify as frequent lucid dreamers (see Table 2).

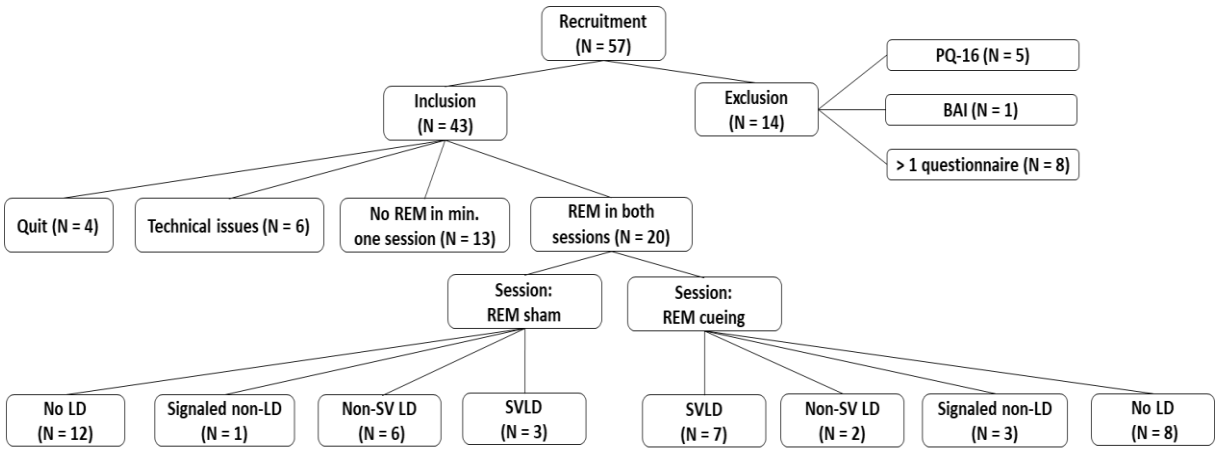

Figure 10. Flowchart of the participant selection process and lucidity-related outcomes for valid participants.

Prior LD frequency (LDF)		2 SVLD sessions	1 SVLD sessions	2 non-SV LD sessions	1 non-SV LD session	1 signaled non-LD session
Never	0	NA	NA	NA	NA	NA
Less than once a year	5	0	1	0	0	1
About once a year	3	0	0	0	0	0
About 2-4 times a year	5	1	3	0	1	1
About once a month	3	0	2	0	2	1
2-3 times a month	0	NA	NA	NA	NA	NA
About once a week	2	0	2	0	1	1
Several times a week	2	0	0	2	0	0
TOTAL	**20**	**1**	**8**	**2**	**4**	**4**

Table 2. Counts of participants with signal-verified lucid dreaming (SVLD), non-signal verified lucid dreams (non-SV LD), and signaled non-lucid dreams (signaled non-LD) sessions during the study as a function of the estimated LD frequency prior to the study.

Overall, we collected 68 valid REM trials: 33 from sham and 35 from cued REM sessions (paired T-test, t = -0.44, p = 0.67). Out of these, 9 (27.27%) and 12 (34.29%) contained lucid experiences, respectively: 3 (33.33%) and 8 (75%) were SVLD, and the remaining were non-SV LD. Although the number of trials resulting in a lucid experience (whether signaled or not) did not differ between sessions as function of the condition, trials including an SVLD experience tended to be more frequent in cued (0.40 ± 0.60) compared to sham REM sessions (0.15 ± 0.37; Wilcoxon sign-rank test, W = 32.0, p = 0.07). Of note, 3 REM trials were reported as signaled by the participants without any detected predefined eye movements (1 sham REM trial and 2 consecutive trials from a single cued REM session), therefore counting as non-SV LD episodes.

Moreover, 4 REM trials (3 cued and 1 sham) presented predefined eye movements that were detected by the scorers without the subjects reporting a lucid episode, thus counting as a signaled non-LD. Two of them were cued REM trials followed by non-lucid dream reports in which the participants acknowledged perceiving sensory cues and responding to them with the predefined eye movement: in one case, the dreamer reported not feeling asleep, while in the other, the signaling was performed in response to the last presented sensory cue immediately before awakening. In the third cued REM trial case, the participant confirmed perceiving and responding to several sensory cues but could not recall the content of the dream experience upon awakening while mentioning a confusional state, again not feeling properly asleep. The last case concerned a sham REM trial resulting in a non-lucid dream report without any mention of signaling intention, which may represent a false LRLR identification by the scorers.

In total, 58 predefined eye movements were detected: 12 were spontaneous (10 occurred during REM sham sessions, and 2 during REM cueing sessions), while 46 were in response to sensory cues (including 7 repeated responses to already signaled cues). Again, we found a trend concerning the frequency of eye movements, which tended to be higher during cued (2.4 ± 6.56) compared to sham REM trials (0.5 ± 1.40; Wilcoxon sign-rank test, W = 44.0, p = 0.09). When exploring the effect of different cue modalities within REM cueing sessions, considering only the first eye signal following each cue, 13 were responses to visual cues, 13 to audio cues, and 13 to tactile ones. The average predefined eye signaling response time to a sensory cue was 6.26 ± 7.86 s (visual: 5.77 ± 8.96 s; auditory: 6.62 ± 6.42 s; tactile: 6.38 ± 8.58 s), with no significant difference between modalities (Friedman test, χ^2 (2) = 0.86, p = 0.65).

Regarding all SVLD trials, 8 included at least two predefined eye movements, thus allowing for a more objective estimation of the episode's duration: 6 cued REM trials and 2 sham REM trials. On average, SVLD episodes lasted 516.38 ± 612.81 s overall (REM cued: 506.33 ± 643.73 s; REM sham: 546.5 s ± 744.58 s), with highly variable durations, ranging from 12 s to 1783 s (see light red highlights in Figure 11). By focusing solely on continuously verified bouts, we were able to discern 9 distinct episodes of continuous SVLD (83.22 ± 70.40 s): 8 during cued REM (91.13 ± 70.87 s), including 31 ocular responses to sensory cues, and 1 during sham REM (20 s), including 2 spontaneous eye signals (see dark red highlights in Figure 11). Unfortunately, the low and uneven number of observations made statistical testing impractical.

Figure 11. Visualization of signal-verified lucid dreams (SVLDs) and their estimated duration for all SVLD trials collected at the IT study site. *The initial verified eye signal in each trial was aligned to t=0, and subsequent eye signals (if any) were plotted sequentially. Continuous (dark red; t: continuously verified time in seconds) and overall (light red; T: overall verified time in seconds) SVLD duration are highlighted. Black markers correspond to spontaneous eye signals, red to visual cue responses, blue to auditory cue responses, and green to tactile cue responses.*

We looked further into DLQ scores (Figure 12), namely regarding ratings for dream awareness (DLQ item #1) and control (DLQ item #4), as well as the total summed score for all DLQ items. Scores were averaged within sessions. Awareness scores showed a trend towards being higher in REM cueing (1.74 ± 1.55) than REM sham sessions (1.3 ± 1.46; Wilcoxon sign-rank test, W = 55, p = 0.07), while the difference in DLQ control ratings between sham (0.56 ± 0.90) and cueing (1.19 ± 1.34) conditions reached significance (Wilcoxon signed-rank test, W = 40.0, p = 0.047), indicating higher dream control in the REM cueing than REM sham condition. Instead, total DLQ scores did not differ significantly between conditions (REM sham: 9.24 ± 9.33; REM cueing: 10.73 ± 9.96; Wilcoxon sign-rank test, W = 78, p = 0.17).

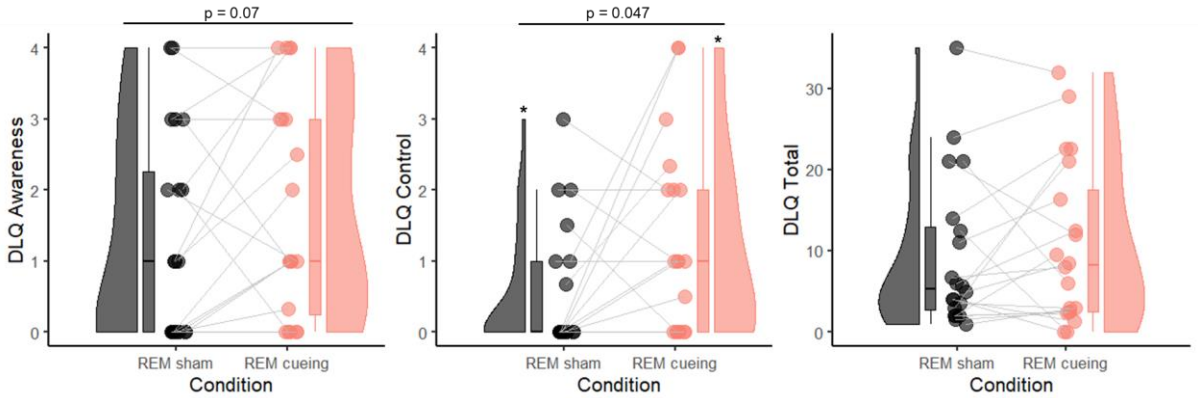

Figure 12. DLQ score distribution for dream awareness (left), dream control (center), and total DLQ score (right), averaged per session, as a function of experimental condition. ** p < 0.05*

We explored potential differences in scores for LuCiD scale factors, averaged within sessions (see Figure 13). When comparing subjects who had at least one LuCiD questionnaire for each session (N = 18/20), we found that the *'memory'* factor was significantly higher in REM cueing (7.38 ± 4.70) than in REM sham (4.93 ± 4.51; paired t-test, t = -0.03, p = 0.04) sessions. There also was a trend for higher *'control'* scores in REM cueing sessions (4.36 ± 5.98) than REM sham sessions (2.49 ± 3.72; Wilcoxon sign-rank test, W = 48, p = 0.09). Differences for all remaining factors remained above significance threshold (*'insight'*: paired T-test, t = -0.74, p = 0.24; *'thought'*: paired T-test, t = -0.69, p = 0.25; *'realism'*: paired T-test, t = -0.93, p = 0.18; *'dissociation'*: Wilcoxon sign-rank test, W = 58, p = 0.14; '*negative emotion*': Wilcoxon sign-rank test, W = 93.5, p = 0.65; '*positive emotion*': paired T-test, t = 0.37, p = 0.64).

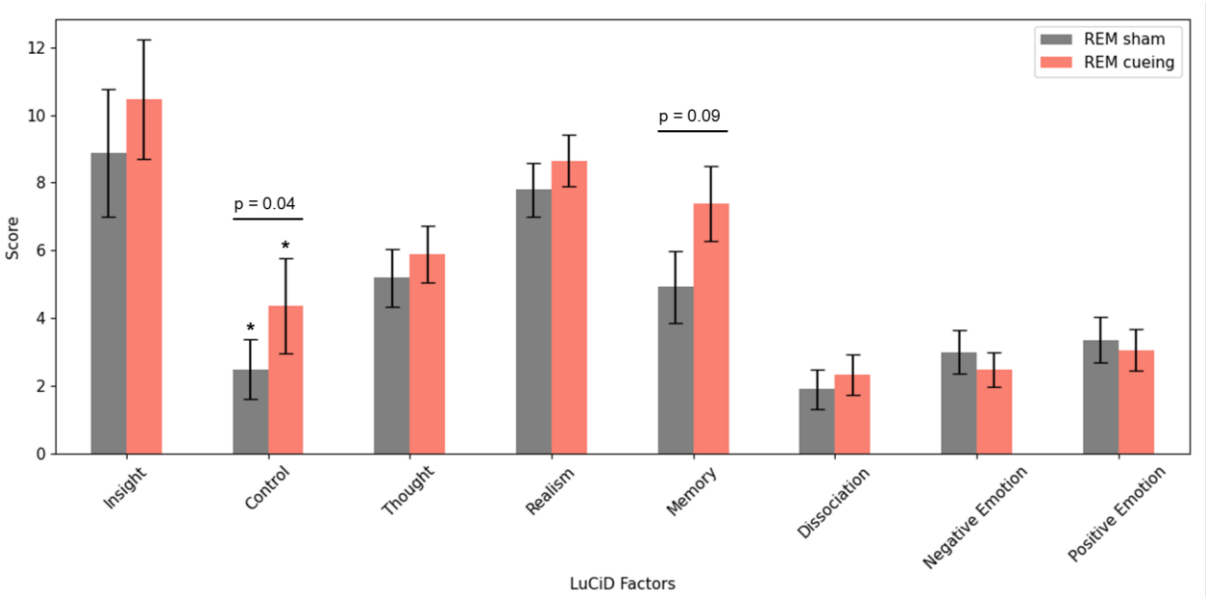

Figure 13. LuCiD factor scores as a function of the experimental condition. *Bars indicate LuCiD factor scores averaged within sessions, along with an indicator of the corresponding standard error. * p < 0.05*

4. Discussion

In this study, we conducted a multi-center lucid dream induction study across three different laboratories using a wearable EEG headband, our dream engineering toolbox, and a combined cognitive-sensory stimulation protocol. Our aim was to address limitations in current literature, including reliance on subjective reports, limited generalizability, and small sample sizes. Once data collection is completed at the CA site, we will achieve the largest sample size for a lucid dream induction study to date, with 60 total participants (20 per site). Our induction method combining SSILD and TLR in morning naps, resulted in lucidity for 65% of participants in the Netherlands and 45% in Italy. However, the impact of REM cueing differed across sites. In NL, LD induction did not differ between conditions (45% cueing vs 35% sham SVLD). Nevertheless, the overall duration of SVLD in the NL site was significantly longer (almost 2.5 times) in the REM cueing condition compared to sham. In the IT site, while the incidence of self-reported LD did not differ between conditions either, the incidence of SVLD was significantly more likely for REM cueing (35%) than REM sham sessions (15%). Moreover, we observed a significant enhancement in dream control ratings in the REM cueing condition compared to sham at the IT site. A more comprehensive conclusion regarding the impact of REM cueing on (SV)LD induction will be provided after combining the datasets from all three sites.

Our results are in line with previous studies, showing that both SSILD and TLR are promising methods to induce LDs. We extend these findings by showing that a combination of both may be beneficial for inducing and maintaining a verified lucid state in dreams. A recent review (Tan & Fan, 2022) examining various techniques for inducing lucid dreams found that the SSILD technique was identified as a 'potentially' successful method with a reasonable success rate (~ 17% of the nights based on subjective reports, Adventure-Heart 2020), but replications are needed. On the other hand, sensory stimulation during REM sleep has yielded somewhat varied findings: while Paul et al. (2014) found visual and tactile stimulation to be ineffective, Erlacher, Schmid et al. (2020) found that auditory stimulation enhanced subjective LD experiences -but not SVLDs- and Carr et al. (2020) reported a high objective success rate when combining visual and auditory stimuli.

In light of this, to improve the efficiency of lucid dream induction, sensory stimulation was integrated as a complement to SSILD. This yielded a higher success rate in our study (55 % SVLD on average, based on 40 participants of the NL and IT sites) compared to previous research: Carr et al. introduced a single-session combined induction method that achieved a 50% SVLD success rate, the highest reported rate thus far. Similarly, Appel et al. (2021) attained a 40% SVLD success rate within 1-2 experimental nights. In contrast, other studies, including those employing longitudinal protocols,

reported relatively lower induction rates. Moreover, when it comes to the methodological quality (Salvesen et al., 2024; Downs & Black, 1998) of peer-reviewed LD induction studies, our methodologies were qualified as moderate (20/25; Stumbrys et al., 2012), while the existing body of literature resulted in poor to moderate quality (89% moderate and 11 % poor according to Tan & Fan, 2022). Furthermore, our study objectively examined the duration of lucidity in two ways (overall and continuous SVLD duration) and demonstrated that our modified method not only increased the rate of lucid dream induction but also prolonged the lucidity period. This method could also be beneficial for researchers attempting to conduct tasks within the context of a lucid dream and thus require a longer LD maintenance duration.

Our preliminary analysis of NL and IT data reveals a high lucidity induction rate, regardless of cueing during REM. Furthermore, the REM cueing procedure showed some effectiveness at increasing dream control, as assessed by the DLQ and the LuCiD scale (trend in the IT site only) . This suggests that our pre-sleep sensory and cognitive training may effectively induce (verified) lucidity, although this possibility would need to be confirmed in future studies including a condition with no SSILD training.

While our approach demonstrated notable effectiveness among moderate-to-highly experienced lucid dreamers, it also yielded a reasonably successful outcome for those with less experience. Out of the total 22 subjects from both NL and IT centers who experienced at least one SVLD during our experimental sessions, we observed the following success rates: 30% (3 out of 10) for individuals with less than yearly lucid dreaming experience, 20% (1 out of 5) for those with approximately yearly experience, 75% (9 out of 12) for individuals with 2-4 times yearly experience, 71% (5 out of 7) for those with approximately monthly experience, and 100% (4 out of 4) for those with weekly experience in lucid dreaming, and 0% (0/2) for those with more than once a week experience. This suggests that our approach may be beneficial for triggering lucid dreams across various levels of prior experience, although it may not significantly contribute to those who are exceptionally experienced.

While REM cueing may not consistently help with lucidity initiation, it may serve as a reliable lucidity “reminder”, as evidenced by the higher number of predefined eye signals in response to sensory cues compared to spontaneous eye signals indicating continued lucidity in absence of cue perception (17 vs. 37, Figure 6, in the NL and 12 vs. 46 at IT site, Figure 11). This lucidity-reminding mechanism may allow a more precise and objective estimation of ‘lucidity duration’ than solely depending on subjective reports, especially in the instances where the captivating content of LD may lead the dreamer to become fully immersed, potentially forgetting to signal lucidity. As a case in point,

considering Figure 6 and the subjective report of P4-S2 (REM sham session), despite experiencing a prolonged period of lucidity, lasting a considerable duration based on the subjective report, there was a gap of approximately 180 s between the last two eye signals. During this time, the dreamer was deeply immersed in the dream content and thus forgot to spontaneously perform eye movements: *"There were pauses in between (doing LRLR) [...] I think in the beginning of being lucid, I tried to do it (LRLR) … more that the dream went on, I just forgot about it to some degree … with the excitement.".* Therefore, we suggest that REM cueing can serve as a means of prompting participants to 'maintain lucidity'. This process establishes predetermined eye signaling milestones, thereby enhancing the precision of estimating objective LD duration.

Although the intensity of our sensory cues was kept relatively low, sensory stimulation may still have interfered in some cases with the sleep and/or dream episode. Unfortunately, the low resolution of our EEG device (2 frontal channels) restrained the possibility of evaluating potential (micro)arousals, namely due to the lack of reliable occipital alpha activity measurement, but PSG recordings at CA site would allow this. In fact, some subjective reports describe the sensory stimulation procedure as detrimental rather than beneficial for the lucid experience: "*I decided to fly a lot. [...] I perceived all of [the stimuli], in a very vivid way. [...] They were almost annoying, in the sense that every time a stimulus arrived, it seemed as if I had to learn to fly again. As if they were bringing me back to reality, you know?* " It is worth noting that this episode was paradoxically the longest recorded SVLD in our sample, with an overall duration of nearly 30 minutes, collected from a participant who had never experienced SVLD before.

Instead, others explicitly mentioned the positive impact of the cueing procedure on initiating and maintaining lucidity: "*As long as [the stimuli] were there, they helped me maintaining that thought and telling myself 'no, it's a dream'. Then I lost [the stimuli], so I started thinking 'wait, then it has to be real [the experience]...".* While these examples are interesting account of the variability of lucidity, they also demonstrate the potential of cueing in initiating and prolonging the SVLD, independently from the subjective assessment of the procedure. Nevertheless, it is possible that cueing is only effective as a 'lucidity reminder' if REM sleep is stable enough, while if REM sleep is not properly consolidated, cue perception may lead to arousal instead of lucidity. This can be the case for shorter lucidity episodes in participants who signaled only once and then immediately woke up. Comparing the characteristics (i.e., phasic/tonic REM, subjective sleep depth) of long and briefer SVLD episodes, such as those in which signaling is shortly followed by awakening, may help to untangle the factors contributing to the maintenance of lucidity.

Concerning the effectiveness of different types of cues, all three evaluated modalities (i.e., visual, auditory, and tactile) seemed to have similar effectiveness. In fact, predefined eye signaling responses rates did not differ across modalities, nor did the response times between the cue and the eye signal differ as a function of the type of cue. Thus, it would seem that the cueing itself is more important than the specific modality.

5. Limitations and prospects

This study demonstrated the effectiveness of our newly developed dream engineering toolbox and a novel lucidity induction technique in prompting lucid dreams with minimal sensing systems. Our objective was to present a comprehensive 'package' comprising the induction technique, minimal equipment requirements, and the software to illustrate the feasibility of achieving an objective lucid dreaming experience without complex measurement tools or prolonged induction methods; however, this came with some limitations.

Our current design did not allow for a clear assessment of the individual impact of SSILD training, or of sensory cueing alone, on inducing lucid dreams. Future studies should include a condition without pre-sleep SSILD training to test whether our high induction rates in the sham condition are in fact due to the combined sensory-cognitive training during wake or to other aspects inherent to our protocol (e.g. sleeping in a novel environment, participating in a lucid dream study, etc.). An additional condition including sensory cues not previously associated with a pre-sleep SSILD training would also help assess the specific influence of sensory stimulation in REM sleep on lucid dream induction.

The use of EEG wearables for sleep recordings also has both limitations and advantages. The lack of occipital EEG in ZMax may have restricted the ability to detect fluctuations in alpha bandpower, thus complicating the distinction between N1 and wake and detection of arousals. Nevertheless, considering the incorporation of the standard polysomnography montage in the CA site, additional assessment on the possibility of Wake vs. N1 staging using ZMax data will be conducted upon the final publication. Having the wearable EEG as the minimal sensing system, however, opens the possibility to replicate the current study over a longitudinal period at home. Conducting such study outside the laboratory would require further enhancement of the automation process, including the development of (1) a reliable artifact rejection algorithm to prevent intervention during periods of poor EEG signal quality, (2) an automatic arousal detection algorithm to adjust stimulus intensity individually based on

ongoing brain activity and subjective arousal thresholds, and (3) a more accurate, near-real-time autoscoring model with a high identification rate for REM sleep, ensuring stimulation is confidently applied only during REM stages and not other sleep phases. Implementing these automated functionalities would not only facilitate various citizen neuroscience projects (Esfahani et al., 2024) on lucid dreaming but also make them accessible with just a consumer-level wearable EEG device and a simple PC. Furthermore, implementing our protocol within the home environment would further raise its methodological quality by increasing the representativeness of the natural context targeted by the study (i.e., external validity).

Also, while the few existing studies using sensory stimulation for LD induction employed open-loop techniques (Antony et al., 2022; Esfahani, Farboud, et al., 2023), future work may also employ a closed-loop stimulation approach by taking the temporal dynamics of the EEG signal into account to enhance the efficacy of REM stimulation targeting (Harrington et al., 2021). This closed-loop method would also prove beneficial in preventing stimulation during instances of low signal-to-noise ratio, as well as when signs of arousal are present. Beyond the potential in SVLD induction, our cueing technique has shown promising results concerning the possibility of signaling the perception (and therefore potential incorporation) of sensory stimuli while dreaming. The possibility of performing eye signaling in both lucid and non-lucid cued episodes provides interesting perspectives for the dream engineering research field, which currently lacks reliable methods for tracking sensory-dependent dream changes (SDDC; Salvesen et al., 2024). In this sense, the use of cueing techniques could represent a valid solution towards the objective measurement of SDDCs, independently from lucidity.

Finally, some accounts have raised concerns regarding possible adverse events of LD. For instance, frequent lucid dreams may in some cases disrupt sleep hygiene, blur the boundaries between wakefulness and sleep, and lead to restlessness or sleep paralysis (Ableidinger et al., 2023; Soffer-Dudek et al., 2020). Nevertheless, recent evidence suggests that lucidity itself does not negatively impacts sleep quality (Stocks et al., 2020; Ribeiro et al.; 2020; Schredl et al., 2020; Stumbrys et al., 2021; Schadow et al., 2018), but rather LD induction attempts that would not lead to lucidity. This highlights the need for developing effective lucid dream induction techniques that mitigate the risk of adverse outcomes while maximizing the benefits. Research efforts such as ours are paving the way towards the validation of more effective, adaptable, and easily implementable LD induction techniques for use in various contexts, ranging from everyday life, to research, and clinical settings.

Acknowledgments

This work was supported by the PPP Allowance made available by Health~Holland, Top Sector Life Sciences & Health. The authors thank Karen Konkoly and Amir Hossein Daraie for their valuable input in the study's early planning stages; Marieke McKenna for recording the English audio track for cognitive training, and Bianca Pedreschi for recording the Italian audio track counterpart.

Author Contributions

Conceptualization: MJE, LACS, CPD, ED, SS, MC, MD; Data curation: MJE, LACS, CPD, TB, TM, BP; Funding acquisition: MD, MC, GB; Methodology: MJE, LACS, CPD, TB, ED, SS, MC, MD; Software: MJE; Validation: MJE, LACS, CPD; Formal analysis: MJE, LACS, CPD, TB, VL; Investigation: MJE, LACS, CPD, VL; Supervision: SS, MC, MD; Visualization: MJE, MJE, LACS, CPD; Writing – original draft: MJE, LACS, VL; Writing – review & editing: MJE, LACS, CPD, TB, TM, ED, VL, BP, GB, PZ, NA, SS, MC, MD.

References

Ableidinger, S., & Holzinger, B. (2023). Sleep Paralysis and Lucid Dreaming—Between Waking and Dreaming: A Review about Two Extraordinary States. Journal of clinical medicine, 12(10), 3437. https://doi.org/10.3390/jcm12103437

Adventure-Heart, D. J. (2020). Findings from the international lucid dream induction study. Frontiers in Psychology, 11, 521520. https://doi.org/10.3389/fpsyg.2020.01746

Allen, M., Poggiali, D., Whitaker, K., Marshall, T. R., van Langen, J., & Kievit, R. A. (2019). Raincloud plots: a multi-platform tool for robust data visualization. Wellcome open research, 4. https://doi.org/10.12688%2Fwellcomeopenres.15191.2

Alvarado, C. S. (1992). The psychological approach to out-of-body experiences: A review of early and modem developments. *The Journal of Psychology*, *126*(3), 237-250. https://doi.org/10.1080/00223980.1992.10543358

Appel, K., Füllhase, S., Kern, S., Kleinschmidt, A., Laukemper, A., Lüth, K., ... & Vogelsang, L. (2020). Inducing signal-verified lucid dreams in 40% of untrained novice lucid dreamers within two nights in a sleep laboratory setting. Consciousness and Cognition, 83, 102960. https://doi.org/10.1016/j.concog.2020.102960

Aspy, D. J. (2017). Studies for the Development of Effective Lucid Dream Induction Techniques.

Attarian HP, Duntley S, Brown KM. Reverse sleep state misperception. Sleep Med 2004;5:269–72. https://doi.org/10.1016/j.sleep.2003.10.014

Baird, B., Riedner, B. A., Boly, M., Davidson, R. J., & Tononi, G. (2019). Increased lucid dream frequency in long-term meditators but not following mindfulness-based stress reduction training. Psychology of Consciousness: Theory, Research, and Practice, 6(1), 40. https://doi.org/10.1037/cns0000176

Baird, B., Tononi, G., & LaBerge, S. (2022). Lucid dreaming occurs in activated rapid eye movement sleep, not a mixture of sleep and wakefulness. Sleep, 45(4), zsab294. https://doi.org/10.1093/sleep/zsab294

Bastien, C. H., Ceklic, T., St-Hilaire, P., Desmarais, F., Pérusse, A. D., Lefrançois, J., & Pedneault-Drolet, M. (2014). Insomnia and sleep misperception. Pathologie Biologie, 62(5), 241-251. https://doi.org/10.1016/j.patbio.2014.07.003

Blanchette-Carrière, C., Julien, S. H., Picard-Deland, C., Bouchard, M., Carrier, J., Paquette, T., & Nielsen, T. (2020). Attempted induction of signalled lucid dreaming by transcranial alternating current stimulation. Consciousness and cognition, 83, 102957. https://doi.org/10.1016/j.concog.2020.102957

Buzzi, G. (2011). False awakenings in light of the dream protoconsciousness theory: A study in lucid dreamers. *International Journal of Dream Research*, *4*(2), 110-116. https://doi.org/10.11588/ijodr.2011.2.9085

Carr, M., Konkoly, K., Mallett, R., Edwards, C., Appel, K., & Blagrove, M. (2020). Combining presleep cognitive training and REM-sleep stimulation in a laboratory morning nap for lucid dream induction. Psychology of Consciousness: Theory, Research, and Practice. https://psycnet.apa.org/doi/10.1037/cns0000227

de Macêdo, T. C. F., Ferreira, G. H., de Almondes, K. M., Kirov, R., & Mota-Rolim, S. A. (2019). My dream, my rules: can lucid dreaming treat nightmares?. Frontiers in Psychology, 10, 486800. https://doi.org/10.3389/fpsyg.2019.02618

Downs, S. H., & Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. Journal of epidemiology & community health, 52(6), 377-384.https://doi.org/10.1136/jech.52.6.377

Dyck, S., Schredl, M., & Kühnel, A. (2017). Lucid dream induction using three different cognitive methods. International Journal of Dream Research, 10(2), 151-156.

Dyck, S., Kummer, N., König, N., Schredl, M., & Kühnel, A. (2018). Effects of lucid dream induction on external-rated lucidity, dream emotions, and dream bizarreness. International Journal of Dream Research, 11(1), 74-78. https://doi.org/10.11588/ijodr.2018.1.43867

Dresler, M., Wehrle, R., Spoormaker, V. I., Koch, S. P., Holsboer, F., Steiger, A., ... & Czisch, M. (2012). Neural correlates of dream lucidity obtained from contrasting lucid versus non-lucid REM sleep: a combined EEG/fMRI case study. Sleep, 35(7), 1017-1020. https://doi.org/10.5665/sleep.1974

Dresler, M., Wehrle, R., Spoormaker, V. I., Steiger, A., Holsboer, F., Czisch, M., & Hobson, J. A. (2015). Neural correlates of insight in dreaming and psychosis. Sleep medicine reviews, 20, 92-99. https://doi.org/10.1016/j.smrv.2014.06.004

Erlacher, D., Schredl, M., & LaBerge, S. (2003). Motor area activation during dreamed hand clenching: A pilot study on EEG alpha band. Sleep and Hypnosis, 5, 182-187.

Erlacher, D., & Schredl, M. (2010). Practicing a motor task in a lucid dream enhances subsequent performance: A pilot study. The Sport Psychologist, 24(2), 157-167. https://doi.org/10.1123/tsp.24.2.157

Erlacher, D., & Stumbrys, T. (2020). Wake up, work on dreams, back to bed and lucid dream: A sleep laboratory study. Frontiers in psychology, 11, 538825. https://doi.org/10.3389/fpsyg.2020.01383

Erlacher, D., Schmid, D., Bischof, F., Hammer, J., & Stumbrys, T. (2020). Ring, ring, ring… Are you dreaming? Combining acoustic stimulation and reality testing for lucid dream induction: A sleep laboratory study. International Journal of dream research, 267-273. https://doi.org/10.11588/ijodr.2020.2.74880

Erlacher, D., Schmid, D., Schuler, S., & Rasch, B. (2020). Inducing lucid dreams by olfactory-cued reactivation of reality testing during early-morning sleep: A proof of concept. Consciousness and cognition, 83, 102975. https://doi.org/10.1016/j.concog.2020.102975

Esfahani, M. J., Carr, M., Salvesen, L., Picard-Deland, C., Demsar, E., Daraie, A.H.,, Keuren, Y., McKenna, M.C., Konkoly, K., Weber, F.D., Schoch, S., Bernardi. G., Dresler, M.schola. (2022). Lucid dream induction with sleep eeg wearables. https://doi.org/10.17605/OSF.IO/U5M3Z

Esfahani, M. J., Daraie, A. H., Zerr, P., Weber, F. D., & Dresler, M. (2023). Dreamento: an open-source dream engineering toolbox for sleep EEG wearables. SoftwareX, 24, 101595. https://doi.org/10.1016/j.softx.2023.101595

Esfahani, M. J., D. Weber, F., Boon, M., Anthes, S., Almazova, T., van Hal, M., ... & Dresler, M. (2023). Validation of the sleep EEG headband zmax. bioRxiv, 2023-08. https://doi.org/10.1101/2023.08.18.553744

Esfahani, M. J., Farboud, S., Ngo, H. V. V., Schneider, J., Weber, F. D., Talamini, L., & Dresler, M. (2023). Closed-loop auditory stimulation of sleep slow oscillations: basic principles and best practices. *Neuroscience & Biobehavioral Reviews*, 105379. https://doi.org/10.1016/j.neubiorev.2023.105379

Esfahani, M. J., Sikder, N., Ter Horst, R., Daraie, A. H., Appel, K., Weber, F. D., ... & Dresler, M. (2024). Citizen neuroscience: wearable technology and open software to study the human brain in its natural habitat. *European Journal of Neuroscience*, *59*(5), 948-965. https://doi.org/10.1111/ejn.16227

Gott, J., Rak, M., Bovy, L., Peters, E., van Hooijdonk, C. F., Mangiaruga, A., ... & Dresler, M. (2020). Sleep fragmentation and lucid dreaming. Consciousness and cognition, 84, 102988. https://doi.org/10.1016/j.concog.2020.102988

Green, C. (1968). Lucid dreams. Oxford: Institute of Psychophysical Research.

Green, C., & McCreery, C. (1994). Lucid Dreaming: The Paradox of Consciousness During Sleep. London: Routledge. https://doi.org/10.4324/9781315812625

Harrington, M.O., Ashton, J.E., Ngo, H.V.V., Cairney, S.A., 2021. Phase-locked auditory stimulation of theta oscillations during rapid eye movement sleep. Sleep 44 (4), zsaa227. https://doi.org/10.1093/sleep/zsaa227.

Holzinger, B., LaBerge, S., & Levitan, L. (2006). Psychophysiological correlates of lucid dreaming. Dreaming, 16(2), 88. https://doi.org/10.1037/1053-0797.16.2.88

Holzinger, B., Saletu, B., & Klösch, G. (2020). Cognitions in sleep: lucid dreaming as an intervention for nightmares in patients with posttraumatic stress disorder. Frontiers in psychology, 11, 558610. https://doi.org/10.3389/fpsyg.2020.01826

Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. Computing in science & engineering, 9(03), 90-95. https://doi.ieeecomputersociety.org/10.1109/MCSE.2007.55

Kern, S., Appel, K., Schredl, M., & Pipa, G. (2017). No effect of α-GPC on lucid dream induction or dream content. Somnologie, 21(3), 180-186. https://doi.org/10.1007/s11818-017-0122-8

Konkoly, K. R., Appel, K., Chabani, E., Mangiaruga, A., Gott, J., Mallett, R., ... & Paller, K. A. (2021). Real-time dialogue between experimenters and dreamers during REM sleep. Current Biology, 31(7), 1417-1427. https://doi.org/10.1016/j.cub.2021.01.026

Kumar, G., Sasidharan, A., Nair, A. K., & Kutty, B. M. (2018). Efficacy of the combination of cognitive training and acoustic stimulation in eliciting lucid dreams during undisturbed sleep: A pilot study using polysomnography, dream reports and questionnaires. International Journal of Dream Research, 11(2), 197-202. https://doi.org/10.11588/ijodr.2018.2.46417

LaBerge, S., LaMarca, K., & Baird, B. (2018). Pre-sleep treatment with galantamine stimulates lucid dreaming: A double-blind, placebo-controlled, crossover study. PLoS One, 13(8), e0201246. https://doi.org/10.1371/journal.pone.0201246

Mallett, R., Sowin, L., Raider, R., Konkoly, K. R., & Paller, K. A. (2022). Benefits and concerns of seeking and experiencing lucid dreams: benefits are tied to successful induction and dream control. Sleep Advances, 3(1), zpac027. https://doi.org/10.1093/sleepadvances/zpac027

Morgenthaler, T. I., Auerbach, S., Casey, K. R., Kristo, D., Maganti, R., Ramar, K., ... & Kartje, R. (2018). Position paper for the treatment of nightmare disorder in adults: an American Academy of Sleep Medicine position paper. Journal of Clinical Sleep Medicine, 14(6), 1041-1055. https://doi.org/10.5664/jcsm.7178

Mota-Rolim, S. A., Pavlou, A., Nascimento, G. C., Fontenele-Araujo, J., & Ribeiro, S. (2019). Portable devices to induce lucid dreams—are they reliable?. Frontiers in neuroscience, 13, 459918. https://doi.org/10.3389/fnins.2019.00428

Paul, F., Schädlich, M., & Erlacher, D. (2014). Lucid dream induction by visual and tactile stimulation: An exploratory sleep laboratory study. International Journal of dream research, 7(1), 61-66.

Picard-Deland, C., Nielsen, T., & Carr, M. (2021). Dreaming of the sleep lab. PloS one, 16(10), e0257738. https://doi.org/10.1371/journal.pone.0257738

Rak, M., Beitinger, P., Steiger, A., Schredl, M., & Dresler, M. (2015). Increased lucid dreaming frequency in narcolepsy. Sleep, 38(5), 787-792. https://doi.org/10.5665/sleep.4676

Ribeiro, N., Gounden, Y., & Quaglino, V. (2020). Is there a link between frequency of dreams, lucid dreams, and subjective sleep quality?. Frontiers in Psychology, 11, 539393. https://doi.org/10.3389/fpsyg.2020.01290

Salvesen, L., Capriglia, E., Dresler, M., & Bernardi, G. (2024). Influencing dreams through sensory stimulation: a systematic review. Sleep Medicine Reviews, 101908. https://doi.org/10.1016/j.smrv.2024.101908

Sandell, C., Stumbrys, T., Paller, K.A. et al. Intentionally awakening from sleep through lucid dreaming. Curr Psychol (2024). https://doi.org/10.1007/s12144-024-05718-x

Saunders, D. T., Roe, C. A., Smith, G., & Clegg, H. (2016). Lucid dreaming incidence: A quality effects meta-analysis of 50 years of research. Consciousness and cognition, 43, 197-215. https://doi.org/10.1016/j.concog.2016.06.002

Saunders, D. T., Clegg, H., Roe, C. A., & Smith, G. D. (2017). Exploring the role of need for cognition, field independence and locus of control on the incidence of lucid dreams during a 12-week induction study. Dreaming, 27(1), 68. https://psycnet.apa.org/doi/10.1037/drm0000044

Schädlich, M., & Erlacher, D. (2018). Practicing sports in lucid dreams–characteristics, effects, and practical implications. Current Issues in Sport Science, 3(7), 1-14. http://dx.doi.org/10.15203/CISS_2018.007

Schadow, C., Schredl, M., Rieger, J., & Göritz, A. S. (2018). The relationship between lucid dream frequency and sleep quality: Two cross-sectional studies. https://doi.org/10.11588/ijodr.2018.2.48341

Schmid, D., & Erlacher, D. (2020). Lucid dream induction by auditory stimulation and reality testing during early-morning sleep. International Journal of dream research, 99-104. https://doi.org/10.11588/ijodr.2020.1.71695

Schredl, M., Dyck, S., & Kühnel, A. (2020). Lucid dreaming and the feeling of being refreshed in the morning: a diary study. Clocks & sleep, 2(1), 54-60. https://doi.org/10.3390/clockssleep2010007

Soffer-Dudek, N. (2020). Are lucid dreams good for us? Are we asking the right question? A call for caution in lucid dream research. Frontiers in neuroscience, 13, 516657. https://doi.org/10.3389/fnins.2019.01423

Spoormaker, V. I., & Van Den Bout, J. (2006). Lucid dreaming treatment for nightmares: a pilot study. Psychotherapy and psychosomatics, 75(6), 389-394. https://doi.org/10.1159/000095446

Standards of Practice Committee, Aurora, R. N., Zak, R. S., Auerbach, S. H., Casey, K. R., Chowdhuri, S., ... & Morgenthaler, T. I. (2010). Best practice guide for the treatment of nightmare disorder in adults. Journal of clinical sleep medicine, 6(4), 389-401. https://doi.org/10.5664/jcsm.27883

Stocks, A., Carr, M., Mallett, R., Konkoly, K., Hicks, A., Crawford, M., ... & Bradshaw, C. (2020). Dream lucidity is associated with positive waking mood. Consciousness and Cognition, 83, 102971. https://doi.org/10.1016/j.concog.2020.102971

Stumbrys, T., Erlacher, D., Schädlich, M., & Schredl, M. (2012). Induction of lucid dreams: A systematic review of evidence. Consciousness and cognition, 21(3), 1456-1475. https://doi.org/10.1016/j.concog.2012.07.003

Stumbrys, T., Erlacher, D., & Schredl, M. (2013). Testing the involvement of the prefrontal cortex in lucid dreaming: a tDCS study. Consciousness and cognition, 22(4), 1214-1222. https://doi.org/10.1016/j.concog.2013.08.005

Stumbrys, T. (2023). Dispelling the shadows of the lucid night: An exploration of potential adverse effects of lucid dreaming. Psychology of Consciousness: Theory, Research, and Practice, 10(2), 152. https://psycnet.apa.org/doi/10.1037/cns0000288

Taitz, I. (2011). Learning lucid dreaming and its effect on depression in undergraduates.

Tan, S., & Fan, J. (2023). A systematic review of new empirical data on lucid dream induction techniques. Journal of sleep research, 32(3), e13786. https://doi.org/10.1111/jsr.13786

Trajanovic, N. N., Radivojevic, V., Kaushansky, Y., & Shapiro, C. M. (2007). Positive sleep state misperception–a new concept of sleep misperception. Sleep Medicine, 8(2), 111-118. https://doi.org/10.1016/j.sleep.2006.08.013

Vallat, R., & Walker, M. P. (2021). An open-source, high-performance tool for automated sleep staging. Elife, 10, e70092. https://doi.org/10.7554/eLife.70092

Voss, U., Holzmann, R., Tuin, I., & Hobson, A. J. (2009). Lucid dreaming: a state of consciousness with features of both waking and non-lucid dreaming. Sleep, 32(9), 1191-1200. https://doi.org/10.1093/sleep/32.9.1191

Voss, U., Schermelleh-Engel, K., Windt, J., Frenzel, C., & Hobson, A. (2013). Measuring consciousness in dreams: the lucidity and consciousness in dreams scale. Consciousness and cognition, 22(1), 8-21. https://doi.org/10.1016/j.concog.2012.11.001

Voss, U., Holzmann, R., Hobson, A., Paulus, W., Koppehele-Gossel, J., Klimke, A., & Nitsche, M. A. (2014). Induction of self awareness in dreams through frontal low current stimulation of gamma activity. *Nature neuroscience*, *17*(6), 810-812. https://doi.org/10.1038/nn.3719

Wickham, H., Chang, W., & Wickham, M. H. (2016). Package 'ggplot2'. Create elegant data visualisations using the grammar of graphics. Version, 2(1), 1-189.

Yount, G., Stumbrys, T., Koos, K., Hamilton, D., & Wahbeh, H. (2023). Decreased posttraumatic stress disorder symptoms following a lucid dream healing workshop. Traumatology. https://doi.org/10.1037/trm0000456

Zink, N., & Pietrowsky, R. (2013). Relationship between lucid dreaming, creativity and dream characteristics. International Journal of Dream Research, 6(3). https://psycnet.apa.org/doi/10.1037/t41936-000

SUPPLEMENTARY MATERIALS

Supplementary Material 1. The full cognitive training protocol.

The cognitive training was presented through a pre-recorded audio track. Each center used different languages for the recording (NL: English; IT: Italian; CA: French and English) while keeping the content, length, and structure identical. The audio track starts with a general definition of lucid dreaming, provides a summary of the cognitive training protocol, and then describes the different fast (2-3 seconds of focus on each of the senses in cyclic order, i.e., vision, hearing, and bodily-sensation exercises) and slow (20 seconds of focus on each of the senses in, cyclic order, i.e., vision, hearing, and bodily-sensation exercises) cycles of SSILD training in detail (Figure 3, Block 1). The first training block instructs participants to perform 4 uncued fast cycles, followed by 4 uncued slower cycles. Afterward, the audio tracks describe the association of the stimuli with the SSILD cycles: light cues with the vision exercises, audio cues with the hearing exercises, and vibration cues with bodily-sensation exercises. Each SSILD exercise (vision, hearing, and bodily-sensations, respectively) lasts one minute and concludes with the administration of the corresponding sensory cue by the experimenter to remind the participant to keep a lucid mindset. The cues also mark the transition from one exercise to the next, with a light cue indicating the end of the vision exercise and the start of the hearing exercise, an audio cue signaling the completion of the hearing exercise and the initiation of the bodily-sensation exercise, and a tactile cue marking the conclusion of the cycle and the start of a new one. During this block, each sensory cue is accompanied by a verbal prompt describing the targeted lucid mindset, as in Carr et al. (2020). Finally, the last block of the cognitive training consists of a repetition of the previous cued SSILD section, with the sole exception that no verbal prompts are played after each cue. As a consequence, participants are expected to transition autonomously from one exercise to another whenever they perceive a cue. Participants are also reminded to perform the predefined LRLR eye movement signaling in cases of lucidity or stimulus perception after falling asleep.

"[Introduction]:

A lucid dream is a dream in which you are aware of the fact that you are dreaming while you are still asleep. With this realization, you can sometimes influence or control what happens in a dream. In this experiment, you'll get instructions on how to practice becoming lucid while awake.

For lucid dreams to occur, you need to train your mind and body into a subtle state that is optimised for lucid dreaming. This involves focusing on your vision, hearing, and bodily sensations in cycles. From this point, we guide you through the training process and describe the practicing cycles. The cycles always start with a vision exercise, then continue towards the hearing exercise, and finally end with the bodily-sensation practices. We describe each of the vision, hearing, and bodily-sensation exercises now:

[Vision exercise]

For the vision exercise, you should keep your eyes closed and focus all your attention on the darkness behind your closed eyelids. Keep your eyes completely still and totally relaxed. You might see colored dots, complex patterns, images, or maybe nothing at all. It doesn't matter what you can or cannot see – just pay attention in a passive and relaxed manner and don't try to see anything.

[Hearing exercise]:

For the hearing exercise, we want you to shift all of your attention to your ears. You might be able to hear the faint sounds of traffic or the wind from outside. You might also be able to hear sounds from within you, such as your own heartbeat or a faint ringing in your ears. It doesn't matter what, if anything, you can hear – just focus all of your attention on your hearing.

[Bodily sensations exercise]:

For the bodily sensations exercise, you should shift all of your attention to sensations from your body. Feel the weight of your blanket, your heartbeat, the temperature of the air, etc. You might also notice some unusual sensations such as tingling, heaviness, lightness, spinning sensations, and so on. If this happens, simply relax, observe them passively and try not to get excited.

Before starting with the first exercise, I would like to mention that you may have intrusive thoughts during this process. For instance, you may think of what you need to buy or do after this experiment. It doesn't matter if the intrusive thoughts come to your mind, but, what matters is that you can intentionally let them go and focus on your body and mind."

Then, the SSILD training (Figure 3, Block 2) was started, which comprised 1 minute of fast cycles practice followed by 4 minutes of short cycles practice:

"Now you should start with the first step of the training. Practice four fast cycles during which you spend only 2-3 seconds focusing each on the vision, hearing, and bodily sensations. You don't have to count the seconds, but you should complete at least 4 cycles during this time. You can start now.

[After 1 min]:

You can stop now. At this point, you should perform four to six slower cycles that approximately take 20 seconds focusing each on the vision, hearing, and bodily sensation steps. Again, you don't have to count the seconds, but you should complete at least 4 cycles during this time. You can start now.

[silence continues for four minutes]"

During the following 12 minutes, the combined SSILD and sensory cueing with additional verbal prompts were presented (Figure 3, Block 3):

"Now, I want to train your mind to recognize the flashing lights, beeping sounds, and vibration cues as lucidity cues so that when one is played during your sleep, you will become lucid in a dream. While you rest here, we are going to play the cues at intervals. Whenever you hear, see, or feel one of the cues, you should remain in the same position with your eyes closed, but you will become lucid by attending to where your mind has been, attending to your body, and attending to your surroundings. The same as before, each cycle starts with vision training. You should continue the vision practice until you see a light cue. Then a prompt will be played to help you focus. Once the prompt is ended you should move forward to the hearing exercise. You should continue the hearing practice until you hear an audio cue. Again, a prompt will be played to help you focus. Once the prompt is ended you should move forward to the bodily-sensations exercise. The vibration cue will indicate when the exercise is ended and then you should start a new cycle. Please note that, as a response to the cues, you do not need to do the Left-right-left-right eye signals while training, only do the eye signals when you become lucid in a dream. You can start with vision practice, now …"

The prompts included:

"[6 x cues (Light-audio-tactile-light-audio-tactile) – 1 min intervals]

[prompt]:

"As you notice the cue, you become lucid. Bring your attention to your thoughts ... [pause] ..., notice where your mind has wandered ...[pause]... Now observe your body ... [pause] ..., your sensations ... [pause] ..., and your feelings... [pause] ... Observe your breathing...[pause]... remain critically aware, lucid, and notice how aspects of this experience are in any way different from your normal waking experience. [pause]

[the next exercise will be started by mentioning the type of the exercise, i.e., vision, hearing, or bodily-sensation]"

The last block of the cognitive training employed an identical SSILD procedure coupled with sensory cueing, with the sole exception that no verbal prompts were played to guide the participant. As a consequence, the participant was expected to transition independently to the subsequent exercise following each cue. The participant was also reminded of doing the predefined LRLR eye movement in case of lucidity during sleep.

"[Instructions after the last prompt (6th cue)]:

The cues will continue to be played in intervals over the next 6 minutes. The prompts, however, will not be played anymore. You should continue to practice becoming lucid by focusing on your vision, hearing, and bodily sensations, the same as before and again in cycles. We keep sending you the cues when you need to move from one exercise to another. Pay attention to your mind, your body, and your surroundings. Notice how aspects of your experience are in any way different from your normal waking experience. At the end of this block, when the cues are stopped, you can fall asleep normally and you don't have to do the exercises anymore. Please keep in mind that when the cognitive training is ended, you should do the left-right-left-right eye signaling in three cases: (1) when you become lucid in a dream, (2) as a response to the cues while being lucid, and (3) approximately every 30 seconds while you are lucid, even though you do not perceive any cue.

Now you can start with the vision exercise…"

[6 cues (2 from each type) should be played in 1-min intervals]

Supplementary Material 2. Evaluation of individual stimulation intensity levels.

The levels of visual and auditory stimuli, as well as the background noise intensity, were determined as follows:

a. Background white noise was set to an unobtrusive volume level, i.e., 35 dbA. The subject was asked whether the volume level was endurable; otherwise, the volume was lowered by 5 dBA. Background white noise was initiated at the start of the experimental nap procedure, before the pre-sleep cognitive training, and was kept constant until the end of the nap session.
b. The audio cue volume was initially set to 40 dBA. While participants were in closed-eye resting wakefulness, the experimenter invited them to judge whether this volume was perceptible and estimate whether it could be arousing if presented during sleep. If the participant agreed that this volume level was non-arousing, the minimum audio volume was set to 40 dBA; otherwise, the experimenter lowered the minimum audio cue volume by 5 dBA and repeated the process until the participant agreed upon the

selected volume. The resulting volume level was set as '**minimum subjective audio volume**'.

c. The lowest light cue intensity was set at 1% in the Dreamento software. Participants were asked to indicate whether they could perceive the light during closed-eye resting wakefulness. If the light cue was not perceived, the experimenters increased the light intensity by 5% until the subjective lowest threshold was reached. The resulting intensity of light was set as '**minimum subjective light intensity**'.

Supplementary Material 2. *The short cognitive training protocol.*

"We do a very short round of training again. The same as before, we want you to practice four fast cycles during which you spend only 2-3 seconds focusing on each of the vision, hearing, and bodily sensations. You don't have to count the seconds, but you should complete at least 4 fast cycles during this time. You can start now.

[40 seconds silence period]:

At this point, you should perform one slower cycle (approximately 20 seconds focusing on each of the vision, hearing, and bodily sensation steps). Again, you don't have to count the seconds, but you should complete at least one cycle during this time. You can start now.

[After 1 min]:

Now, the same as before, we will play the cues at intervals. You should continue to practice becoming lucid by focusing on your vision, hearing, and bodily sensations in cycles. Whenever you need to move from one exercise to the next, you will receive the corresponding cue. At the end of this block, when the cues are stopped, you can fall asleep normally and you don't have to do the exercises anymore. Please keep in mind that you should do the Left-right-left-right eye signaling in three cases: (1) when you become lucid in a dream, (2) as a response to the cues while being lucid, and (3) approximately every 30 seconds while you are lucid even though you do not perceive any cue. Now you can start with the vision exercise…"

[3 mins silence: play the light, audio, and vibration cues in 1-min intervals] "

Supplementary Material 3. Experimental interruptions

In some cases, the experimenters needed to interrupt the experiment:

A. If the participant could not fall asleep within the first hour, experimenters could briefly interrupt the nap session based on a case-per-case decision, depending on factors such as the level of subjective anxiety, tossing and turning, or following specific requests from the participant. The experimenter interacted with the participants through the intercom system

to ask whether they required anything (e.g., drinking water, or going to the bathroom). If the participant asked to use the bathroom, the experimenter unplugged the EMG electrodes from the amplifier and, if needed, helped the participant take the EEG headband off. The experimenter tagged this period on the recording with the corresponding marker.

B. Whenever a sudden signal loss was identified (e.g., EEG disconnection or very high noise in EMG channels indicating electrode detachment), the participant was asked to adjust the corresponding electrodes to ensure they were completely in contact with the skin via the intercom system. If signal loss happened while the participant was asleep, the experimenter waited until either spontaneous movement during sleep fixed the issue or until the next full arousal to interact with the participant. If the participant was not able to solve the problem, the experimenter entered the experimental room to assist in fixing the problem.

Supplementary Material 4. Dream Interviewing

The dream interviewing occurred during the following cases:

1. *Waking up from REM sleep (e*ither upon spontaneous awakening or induced awakening due to REM period termination).
2. *Upon experimental interruptions (e.g., the* participant asked for a break, or a technical issue due to poor signal quality).
3. *At the very end of the experimental nap session (*upon termination of the last nap trial of the session due to time constraints, even if they were physiologically awake/non-REM).
4. *Based on the participant's report of a LD* (whenever the participant experienced a LD, even if this occurred in a non-REM sleep state).
5. *Observing predefined eye signals during non-REM (*whenever a predefined eye signal was identified by the experimenters during non-REM sleep, the participant was awakened ~20 seconds after eye signaling stopped; of note, if the predefined eye signals were observed during REM, the experimenter waited until REM period termination).

Supplementary Material 5. Exploring diverse experiences beyond lucidity

Aside from lucidity itself, we anticipated that our LD induction methods might trigger other LD-related phenomena. Dream reports were scored on the occurrence of the following phenomena:

- Lab incorporation dreams (LID): Participants dream about the laboratory, such as being in or around the laboratory, perceiving electrodes and other lab objects, or interacting with experimenters (Picard-Deland et al., 2021).
- False Awakenings (FAs): A specific case of LID, where participants dream that they wake up within their dreams (e.g. waking up in the lab)(Green, 1968; Green & McCreery, 1994; Buzzi et al., 2011).
- Sleep misperception (SM): cases where participants "misperceived" their *sleep*, i.e. reported being awake despite physiological signals indicating sleep activity (confirmed through post-hoc analysis) (Bastien et al., 2014; Trajanovic et al., 2007).
- Reverse sleep misperception (RSM): Participants who “misperceived” their *waking* state, perceiving themselves as asleep despite physiological signals indicating wakefulness (Attarian et al., 2003; Trajanovic et al., 2007).
- Sleep Paralysis (SP): the experience of being temporarily unable to move or talk (muscle atonia), often occurring in the transitions between sleep and wakefulness and sometimes accompanied by vivid sensory or mental experiences.
- Out-of-body experiences (OBE): the dreams where the participants observed their body from outside (Alvarado, 1992).

In exactly half of the sessions, three quarters of the participants (15/20) reported lab incorporated dream (LID) scenarios that involved aspects of the experimental session, including the lab bedroom: “...here was another door in this room. I was in this room”, wires/electrodes: “The wires that are like on my face and neck and stuff. We're on the other side of the bed.”, interactions with the researchers: “I thought I was actually interacting with you (experimenter). And, in this, well, it should be in some place like the institute, but it looks a lot like a mall”, and other experiment related details. LIDs frequently co-occurred with instances of false awakenings (FA), where some participants had the experience of waking up within the dream: “So I woke up from a dream, and you guys were like, let's go, so we went to like a like in the building, to a dog show….”. Out of all FA, only one was reported without LID experience. These phenomena will be further analyzed in the future work.

Two instances of sleep paralysis, one in a stimulation session and one in a control session, were reported by two different participants recalling that they could not move their body in their dream experience: “So like, in my dream. It felt like I did couldn't move any more. I said it was still sleeping except I would I like ….heard … stuff going on and I could even see what was happening, even though my eyes were still closed. ”. One of these participants also experienced seeing themselves

outside their body: “I can also just see myself that my eyes were closed. So I guess it was more like as if I was watching from some other four persons' point of view”. While the SP and OBE occurrences will be discussed in future work, with a primary emphasis on dream analysis, this paper demonstrates that our proposed induction technique led to low rates of SP and OBE, phenomena commonly recognized as detrimental factors to sleep quality and negative outcomes of lucid dreaming.

Supplementary Tables

Supplementary Table 1. Initial inclusion and exclusion criteria of the study.

Inclusion criteria	Exclusion criteria
- Healthy; - Able to provide written consent prior to admission; - Aged 18 - 55 years; - Regular sleep-wake patterns on workdays; - Experienced at least one lucid dream in life; - High dream recall frequency (min. 3 recalls per week).	- Current or past diagnosis of neurological, psychiatric or neurodegenerative diseases; - History of sleep disorders (insomnia, sleep apnea, nightmare disorder, circadian rhythm disorders, somnambulism); - Chronic or acute physical or psychological condition known to affect sleep quality - Prior head/brain surgery; - Suffering from Epilepsy; - Pregnancy; - Using psychotropic or sleep medication.

Supplementary Table 2. Questionnaires during different phases of the study.

Phase	***Assessment topic***	***Questionnaires***
Intake session	*Sleep-wake cycle*	*- Pittsburgh Sleep Quality Index (PSQI)*
		- Morningness-Eveningness Questionnaire (MEQ)
	Dreams	*- Mannheim Dream Questionnaire (MADRE)*
	Emotional processing and psycho-affective functioning	*- Beck Anxiety Inventory (BAI)*
		- Beck Depression Inventory (BDI-II)
		- Prodromal Questionnaire 16-item version (PQ-16)
	Potential confounding variables	*- Vividness of Visual Imagery Questionnaire (VVIQ)*
Daily diary	*Dream Lucidity*	*- Dream Lucidity Questionnaire (DLQ)*
	Dream content and sleep quality	*- Daily Sleep and Dream Questionnaire*
During experimental session	*Dream Lucidity*	*- Dream Lucidity Questionnaire (DLQ)*
	Dream / experience content	*- Semi-structured interviewing*

At the end of experimental session	*Dream Lucidity*	*- Lucidity and Consciousness in Dreams Scale (LuCiD)*
	Dream / experience content	*- Brief explanation for each experience*
Exit survey (optional)	*Dream Lucidity*	*- Changes in lucid dreaming frequency*

Supplementary Table 3 - Exclusion criteria, measure, and contingency at the intake session. *BAI: Beck Anxiety Inventory. BDI: Beck Depression Inventory. PSQI: Pittsburgh Sleep Quality Index. REM: Rapid Eye Movement.*

Stage of assessment	**Tested factor**	**Measure**	**Criteria**	**Contingency**
Intake	Current sleep problems	PSQI	Score > 7	Recruit new participant
Intake	Depression	BDI-II	Score ≥ 20	Recruit new participant
Intake	Anxiety	BAI	Score > 15	Recruit new participant
Intake	Dream Recall Frequency	Screening	Dream recall frequency < 3 times a week	Recruit new participant
Intake	Risk for developing psychosis	Prodromal questionnaire	Score ≥ 9	Recruit new participant
Intake	Chronotype	Screening	Sleep time before 23:00 / Rise time before 07:00 on the weekday (s) of the experimental sessions	Recruit new participant
Experimental data	Technical problems	All data	Unsolvable technical problems before the pre-sleep training	Reschedule
Experimental session	Experimental condition implementation	Online REM sleep detection in both experimental sessions	No (REM) sleep during one experimental session	Recruit new participant

***Supplementary Table 4* - Cueing protocol during the initial cognitive training period.** Cognitive training blocks correspond to the ones highlighted in Figure 3. The timing of each cue within the cognitive training and their corresponding physical characteristics (i.e., repetition, onset/offset, intensity) are described in Table 3. The first six cues belong to the third block (i.e., SSILD + sensory cueing + prompts), and the last six correspond to the last block of cognitive training (i.e., SSILD + sensory cueing). The cues were played in cyclic order, mirroring the SSILD exercises, and their intensities (light and audio cues) or number of repetitions (vibration cue) followed a sequentially decreasing pattern from the first to the last cycle. Individual thresholds were accounted for, and stimulus intensity (light and audio cues) was adjusted based on the previously defined subjective thresholds.

Cue number	Type	Features	Cogntive training block
1	Light	RED – 3 reps - 500 ms on/off - Minimum subjective intensity + 15%	3
2	Audio	500-700-900 Hz , 200 ms on/off - Minimum subjective volume + 15 dBA	3
3	Vibration	All colors set to zero, 3 reps, 200 ms on / 500 ms off	3
4	Light	RED – 3 reps - 500 ms on/off - Minimum subjective intensity + 10%	3
5	Audio	500-700-900 Hz , 200 ms on/off - Minimum subjective volume + 10 dBA	3
6	Vibration	All colors set to zero, 2 reps, 200 ms on / 500 ms off	3
7	Light	RED – 3 reps - 500 ms on/off - Minimum subjective intensity + 5%	4
8	Audio	500-700-900 Hz , 200 ms on/off - Minimum subjective volume + 5 dBA	4
9	Vibration	All colors set to zero, 2 reps, 200 ms on / 500 ms off	4

10	Light	RED – 3 reps - 500 ms on/off - Minimum subjective intensity	4
11	Audio	500-700-900 Hz , 200 ms on/off - Minimum subjective volume	4
12	Vibration	All colors set to zero, 1 rep, 200 ms on / 500 ms off	4

Supplementary Table 5 - Cueing protocol during the short cognitive training following each (intermediate) awakening.

Cue number	***Type***	***Features***
1	*Light*	*RED – 3 reps – 500 ms on/off* -Minimum subjective intensity *+ 5 %*
2	*Audio*	*500-700-900 Hz , 200 ms on/off* - Minimum subjective *volume + 5 dBA*
3	*Vibration*	*All colors set to zero, 2 reps, 200 ms on 500 ms off*

Supplementary Table 6 - Annotations during the experimental session. *The experimenters were continuously monitoring the signals in real-time and set various annotations accordingly.*

Occasion	**Markers**
Upon the start of data recording	- White noise sound level checked. - Cognitive training sound level checked. - Audio cue lowest sound level checked (value:). - Light cue lowest intensity checked (value:).
Calibration	- Calibration started (1 min relax) - clench 3x - Predefined eye movement checked. - Calibration ended.
Cognitive training	- Cognitive training started. - Cognitive training ended.
Upon sleep onset	- Sleep onset. - Sleep onset already while training
Upon REM detection	- Suspicious to REM - REM detected. - Predefined LRLR detected.
Sham conditions	- sham - light - sham - audio - sham - vibration - SVLD detected - suspicous to LRLR - cueing delayed - signs of arousal
While awakening	- Awakening. - Structured interview started. - Structured interview ended. - Questionnaires record started. - Questionnaires record ended. - clench 3x.
While falling sleep after awakening	- Short cognitive training started. - Short cognitive training ended.
Upon subjective request	- Subjects wants to go to bathroom. - Subject came back from bathroom. - Subjects needs water. - clench 3x.
Noisy EMG channel	- EMG x noisy - decisions based on EMG xx
Upon experimental interruption	- Bad signal quality - asking the subject to ... - Subject could not fall asleep in last 1 hour. - Asking if subject needs something. - clench 3x
Upon the end of experiment	- Experimental time ended - final report

Supplementary Table 7 - Inter-rater agreement for identifying dream lucidity at the NL centre. *In the "Overall Lucidity Evaluation Consensus" column, cases were categorized based on whether both subjective reports and signals confirmed lucidity, resulting in the designation of Signal-Verified Lucid Dream (SVLD). Cases where subjective lucidity reports lacked verified eye signals were labeled as non-signal verified lucid dream (non-SV LD). Instances where raters agreed on the presence of signal verification without subjective reports of lucidity were marked as signaled non-LD, while the absence of both subjective and objective lucidity measures was denoted by "X". In the "Number of Predefined Eye Movements Consensus" column, the consensus among scorers for each detected eye signal was made. The "Predefined Eye Signals and Cueing Association" column indicates whether the eye signaling was confirmed to be in response to a light cue (L), auditory cue (A), vibration (V), or if it occurred spontaneously (S) without any nearby cue. X: disagreement. X*?: Ambiguous cases leaning towards disagreement. Y*?: Ambiguous cases leaning towards agreement. Y: agreement. FA: false awakening. LID: lab incorporated dream. SM: sleep misperception. RSM: reverse sleep misperception. SP: sleep paralysis. OBE: out-of-body experience.*

				Sleep scoring		Lucidity assessment					Beyond lucidity					
Subject ID	**Session**	**Type**	**Prior LD experience**	**Kappa score (%)**	**Kappa score combining W & N1(%)**	**Subjective LD report**	**Signal verification consensus**	**Overall lucidity evaluation consensus**	**Number of predefined eye movements consensus**	**Predefined eye signals and cueing association**	**FA**	**LID**	**SM**	**RSM**	**SP**	**OBE**
NL_DNDRS_0002	1	REM cueing	about once a month	*0.7*	*0.77*	x	x	x			x	x	Y	x	x	x
	2	REM sham		*0.76*	*0.78*	Y	Y	SVLD	Y (1/1)	S	x	x	x	x	x	x
NL_DNDRS_0003	1	REM sham	about once a month	*0.68*	*0.67*	Y	x	non-SVLD			x	x	Y	x	x	x
	2	REM cueing		*0.72*	*0.79*	Y	Y	SVLD	xxYYYYxY (5/8)	LVLVV	x	Y	Y	x	x	x
NL_DNDRS_0004	1	REM cueing	less than once a year			x	x	x			x	x	Y	x	x	x
	2	REM sham		*0.81*	*0.91*	Y	Y	SVLD	xYYYYxx (4/7)	SSSS	Y	Y	x	x	x	x
NL_DNDRS_0005	1	REM sham	about two to four times a year	*0.8*	*0.91*	Y	x	non-SVLD			x*?	Y	Y	x	x	x
	2	REM cueing		*0.79*	*0.88*	x	x	x			x	x	Y	x	x	x
NL_DNDRS_0006	1	REM sham	about two to four times a year	*0.86*	*0.93*	Y	x	non-SVLD			Y	Y*?	x	x	x	x
	2	REM cueing		*0.66*	*0.79*	Y	x	non-SVLD			x	x	x	x	x	x
NL_DNDR	1	REM	about	*0.71*	*0.93*	Y	Y	SVLD	YYY (3/3)	LAV	Y	x	Y*?	x	x	x

S_0008		cueing	two to four times a year													
	2	REM sham		*0.71*	*0.91*	Y	Y	SVLD	YYxY (3/4)	SSS	Y	Y	x	x	x	x
NL_DNDRS_0009	1	REM sham	less than once a year	*0.73*	*0.84*	Y	x	non-SVLD	x (0/1)		x	Y	x	x	x	x
	2	REM cueing		*0.89*	*0.97*	Y	Y	SVLD	xxxYxYxxx (2/10)	VV	Y	Y	x	x	x	x
NL_DNDRS_0011	1	REM sham	less than once a year	*0.73*	*0.92*	Y	x	non-SVLD			x	x	x	x	x	x
	2	REM cueing		*0.67*	*0.83*	x	x	x			x	x	Y	x	x	x
NL_DNDRS_0013	1	REM cueing	about two to four times a year	*0.55*	*0.68*	Y	x	non-SVLD			x	Y	x?*	x	x	x
	2	ctrl.		*0.65*	*0.89*	Y	Y	SVLD	Y (1/1)	S	x*?	x	Y*?	x	x	x
NL_DNDRS_0014	1	REM cueing	about once a month	*0.65*	*0.96*	Y	Y	SVLD	YYYYYYYYY Y (10/10)	LAVL SVVA VL	x	x	x	x	x	x
	2	REM sham		*0.78*	*0.96*	Y	Y	SV	Yxx (1/3)	S	x	x	x	x	x	x
NL_DNDRS_0015	1	REM sham	about once a year	*0.78*	*0.84*	x	Y	SV	xxYxxxxx (1/8)	S	x	x	x	x	x	x
	2	REM cueing		*0.72*	*0.77*	x	x	x			x	Y	x	x	x	x
NL_DNDRS_0018	1	REM cueing	less than once a year	*0.77*	*0.82*	x	x	x			Y	Y	x	x	Y	Y
	2	REM sham		*0.73*	*0.75*	x	x	x			x	Y	x	x	x	x
NL_DNDRS_0021	1	REM sham	about once a week	*0.6*	*0.6*	Y	x	LD	xxxx (0/4)		x	x	x	Y	Y	x
	2	REM cueing		*0.44*	*0.4*	Y	Y	SVLD	xYxYY (3/5)	LAV	Y	Y	x	x	x	x
NL_DNDRS_0022	1	REM cueing	less than once a year	*0.69*	*0.82*	x	x	x			x	x	x	x	x	x
	2	REM sham		*0.79*	*0.89*	x	x	x			x	Y	x	x	x	x
NL_DNDR	1	REM	about	*0.58*	*0.8*	Y	Y	SVLD	Y (1/1)	A	Y	Y	Y	x	x	x

S_0024		cueing	two to four times a year													
	2	REM sham		*0.77*	*0.92*	x	x	x			x	Y	x	x	x	x
NL_DNDR S_0026	1	REM sham	about once a month	*0.6*	*0.9*	Y	x	non-SV LD			x	x	x	x	x	x
	2	REM cueing		*0.52*	*0.78*	Y*	x	non-SV LD			x	x	Y	x	x	x
NL_DNDR S_0028	1	REM cueing	about once a year	*0.24*	*0.62*	Y	Y	SVLD	Y (1/1)	A	x	x	x	x	x	x
	2	REM sham		*0.76*	*0.85*	x	x	x			x*?	x	Y*?	x	x	
NL_DNDR S_0030	1	REM cueing	about two to four times a year	*0.71*	*0.94*	Y	Y	SVLD	YYYxxYYYY Y (8/10)	LALL ALAA	x	x	Y*?	x	x	x
	2	REM sham		*0.77*	*0.91*	Y	Y	SVLD	xxxYY (2/5)	SS	Y	Y	x	x	x	x
NL_DNDR S_0032	1	REM sham	about two to four times a year	*0.64*	*0.79*	Y	Y	SVLD	xYY (2/3)	SS	Y	Y	x	x	x	x
	2	REM cueing		*0.7*	*0.79*	x	x	x			Y	Y	x	x	x	x
NL_DNDR S_0033	1	REM sham	about once a week	*0.55*	*0.7*	Y	Y	SVLD	xYY (2/3)	SS	x	Y	x	x	x	x
	2	REM cueing		*0.76*	*0.88*	Y	Y	SVLD	YYxYxYYY (6/8)	SALA LAL	Y	Y	x	x	x	x

Supplementary Table 8 - Inter-rater agreement outcomes for sleep and dream lucidity identification at the IT centre. *A: Auditory-cued eye movement response, L: Light-cued eye movement response, Non-SV LD: Non-signal-verified lucid dream, Signaled non-LD: Signaled non-lucid dream, SVLD: Signal-verified lucid dream, S: Spontaneous eye movement signaling, V: Vibration-cued eye movement response, X: absent/disagreement, Y: present/agreement.*

Subject ID	Session	Type	Prior LD experience	Sleep scoring		Lucidity assessment				
				Kappa score (%)	Kappa score combining W & N1 (%)	Subjective LD report	Signal verification consensus	Overall lucidity evaluation consensus	Number of predefined eye movements consensus	Predefined eye signals and cueing association
IT_IMT_P0007	1	REM sham	Less than once a year	0.86	0.96	X	X	X		
	2	REM cueing		0.76	0.91	X	X	X		
IT_IMT_P0008	1	REM cueing	Less than once a year	0.71	0.83	X	X	X		
	2	REM sham		0.76	0.93	X	Y	signaled non-LD	Y (1/1)	S
IT_IMT_P0012	1	REM sham	Less than once a year	0.7	0.89	X	X	X		
	2	REM cueing		0.85	0.91	X	X	X		
IT_IMT_P0016	1	REM cueing	Several times a week	0.53	0.7	Y	X	non-SV LD		
	2	REM sham		0.77	0.91	Y	X	non-SV LD	X (0/1)	S
IT_IMT_P0022	1	REM sham	About once a year	0.74	0.84	X	X	X		
	2	REM cueing		0.88	0.94	X	X	X		
IT_IMT_P0023	1	REM cueing	About 2-4 times a year	0.57	0.77	Y	Y	SVLD	YYYYYYYYYYYYYYYYYYYYYYYYYYY (29/29)	VVATATAAAAAAATVATATTAVATVATVS

	2	REM sham		0.56	0.62	X	X	X		
IT_IMT_P0024	1	REM sham	Less than once a year	0.69	0.88	X	X	X		
	2	REM cueing		0.65	0.73	Y	Y	SVLD	Y (1/1)	V
IT_IMT_P0025	1	REM cueing	Less than once a year	0.54	0.84	X	X	X		
	2	REM sham		0.6	0.94	X	X	X		
IT_IMT_P0028	1	REM sham	Several times a week	0.38	0.75	Y	X	non-SVLD		
	2	REM cueing		0.52	0.69	Y	X	non-SVLD		
IT_IMT_P0030	1	REM sham	About 2-4 times a year	0.78	0.87	Y	Y	SVLD	Y (1/1)	S
	2	REM cueing		0.81	0.9	X	X	X		
IT_IMT_P0036	1	REM cueing	About 2-4 times a year	0.66	0.84	Y	Y	SVLD	YYYYYYYY (8/8)	SVVVATVA
	2	REM sham		0.72	0.85	Y	X	non-SVLD		
IT_IMT_P0038	1	REM sham	About once a year	0.77	0.86	X	X	X		
	2	REM cueing		0.68	0.86	X	X	X		
IT_IMT_P0039	1	REM cueing	About once a month	0.46	0.6	Y	Y	SVLD	Y (1/1)	S
	2	REM sham		0.43	0.45	Y	X	non-SVLD		
IT_IMT_	1	REM	About once	0.62	0.75	Y	X	non-SV		

P0041		sham	a month					LD		
	2	REM cueing		0.57	0.71	X	Y	signaled non-LD	Y (1/1)	A
IT_IMT_ P0044	1	REM cueing	About 2-4 times a year	0.81	0.92	X	X	X		
	2	REM sham		0.78	0.9	X	X	X		
IT_IMT_ P0051	1	REM cueing	About 2-4 times a year	0.55	0.92	Y	Y	SVLD	YY (2/2)	AT
	2	REM sham		0.7	0.96	Y	Y	SVLD	YYX (2/3)	SS
IT_IMT_ P0052	1	REM cueing	About once a year	0.51	0.79	X	X	X		
	2	REM sham		0.65	0.75	X	X	X		
IT_IMT_ P0054	1	REM cueing	About once a week	0.82	0.9	Y	Y	SVLD	XYYYY (4/5)	VATV
	2	REM sham		0.84	0.9	X	X	X		
IT_IMT_ P0055	1	REM sham	About once a week	0.73	0.96	Y	X	non-SV LD		
	2	REM cueing		0.59	0.74	Y	Y	SVLD	YY (2/2)	ST
IT_IMT_ P0056	1	REM sham	About once a month	0.79	0.94	Y	Y	SVLD	YYYYYY (6/6)	SSSSSS
	2	REM cueing		0.63	0.81	X	X	X		

Supplementary Table 9. Item-by-item scores for the adapted methodological assessment checklist. *R: reporting, EV: external validity, IV-B: internal validity (bias), IV-C: internal validity (confounding), P: power.*

		Item	Score	(max score)
R	1	*Is the hypothesis/aim/objective of the study clearly described?*	1	1
R	2	*Are the main outcomes to be measured clearly described in the Introduction or Methods section?*	1	1
R	3	*Are the characteristics of the subjects included in the study clearly described?*	1	1
R	4	*Are the interventions of interest clearly described?*	1	1
R	5	*Is there an adequately defined baseline or control condition?*	1	1
R	6	*Are the main findings of the study clearly described?*	1	1
R	7	*Does the study provide estimates of the random variability in the data for the outcomes of interest?*	1	1
R	8	*In cases where experimental trials have been excluded from the analyses, have the exclusion criteria been provided?*	1	1
R	9	*In cases where subjects have been excluded from the analyses, have the exclusion criteria been provided?*	1	1
R	10	*Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is < 0.001?*	1	1
EV	11	*Is the sampling procedure described?*	1	1
EV	12	*Is the sampling procedure unbiased?*	1	1
EV	13	*Is the experimental setting representative of the natural context targeted by the study ?*	0	2
IV/B	14	*Was an attempt made to blind study subjects to the intervention they have received ?*	1	1
IV/B	15	*Was an attempt made to blind those measuring the main outcomes of the intervention?*	0	1
IV/B	16	*If any of the results of the study were based on "data dredging", was this made clear?*	1	1
IV/B	17	*Is the experimental duration (e.g. number of experimental sessions, number of trials, etc.) comparable for all subjects?*	1	1
IV/B	18	*Were the statistical tests used to assess the main outcomes appropriate?*	1	1
IV/B	19	*Were the main outcome measures accurately defined, valid, and reliable?*	2	2
IV/C	20	*Were appropriate randomization procedures applied to the experimental conditions/groups?*	1	1
IV/C	21	*Was there adequate adjustment for potential/known confounding effects in the analyses from which the main findings were drawn?*	1	1
P	22	*Has any power calculation been performed and described?*	0	1
P	23	*Have appropriately chosen effect sizes been reported?*	0	1
		TOTAL	**20**	25

Supplementary Table 10. Evaluation of sleep metrics for participants who experienced at least one REM episode in both experimental sessions. *The values are shown in mean ± std format. In the NL site, only the latency of N2 sleep was significantly higher during REM cueing condition. The non-significant difference between the majority of sleep statistics (e.g., sleep efficiency and sleep maintenance efficiency) remained intact, showing that our induction technique did not disturb sleep.*

	NL site		**IT site**	
	Session type			
Metrics	**REM cueing**	**REM sham**	**REM cueing**	**REM sham**
TIB (min)	187.55 ± 15.19	186.5 ±12.11	196.3 ± 13.83	190.68 ± 15.12
SPT (min)	151.8 ± 17.96	160.68 ± 17.20	164.03 ± 16.13 **	151.65 ± 16.2 **
WASO (min)	58.55 ± 21.38	55.93 ± 19.67	45.68 ± 19.33	41.43 ± 15.58
TST (min)	90.65 ± 26.53	103.23 ± 25.11	117.93 ± 26.82	109.85 ± 22.49
N1 (min)	30.18 ± 17.60	28.25 ± 12.40	37.2 ± 25.04	27.13 ± 16.32
N2 (min)	46.9 ± 17.96	50.38 ± 18.32	55.2 ± 19.59	60.78 ± 19.31
SWS (min) †	2.1 ± 6.21	7.6 ± 10.06	9.23 ± 11.31	6 ± 10.44
REM (min)	11.48 ± 10.89	17 ± 11.35	16.3 ± 10.97	15.95 ± 10.87
NREM (min)	79.175 ± 25.93	86.23 ± 20.57	101.63 ± 28.15	93.9 ± 19.42
SOL (min)	20.5 ± 13.95	17.15 ± 10.12	24.55 ± 10.89	30.75 ± 17.03
Latency N1 (min)	20.5 ± 13.95	18.0 ± 11.67	24.55 ± 10.89	32.2 ± 19.34
Latency N2 (min)	49.8 ± 30.57 ***	34.75 ± 13.35 ***	42.93 ± 24.85	41.43 ± 14.35
Latency SWS (min) †	89.88 ± 41.01	118.55 ± 50.24	119.7 ± 46.08	124.72 ± 49.21
Latency REM (min)	95.4 ± 36.98	84.08 ± 31.96	91.6 ± 38.63	84.08 ± 41.43
N1 (%)	33.72 ± 17.77	28.26 ± 12.51	31.95 ± 20.41	25.86 ± 17.29
N2 (%)	51.89 ± 16.27	49.26 ± 16.21	46.49 ± 11.78 *	54.95 ± 14.51 *
SWS (%) †	1.85 ± 5.38	6.67 ± 9.29	7.32 ± 9.33	5.25 ± 8.82
REM (%)	12.54 ± 11.25	15.81 ± 9.54	14.25 ± 10.08	13.94 ± 8.57
NREM (%)	87.46 ± 11.25	84.19 ± 9.54	85.75 ± 10.08	86.06 ± 8.57
SE (%)	48.65 ± 14.25	55.38 ± 12.99	59.71 ± 12.11	57.76 ± 11.6

SME (%)	59.42 ± 14.29	64.08 ± 12.70	71.37 ± 13.25	72.12 ± 11.67

*†: In the NL site, only 11 sessions in the REM sham and 4 in REM cueing conditions included SWS, while in the IT site, 9 sessions in the REM sham and 10 in REM cueing condition did. Therefore, measures related to SWS were excluded from statistical analysis. *: P < 0.05 , **: P < 0.01, ***: P < 0.001. SPT: sleep period time, TST: total sleep time, SE: sleep efficiency, SME: Sleep maintenance efficiency, SOL: sleep onset latency, WASO: wake after sleep onset, Lat: latency. Values are represented in the form of mean ± standard deviation.*