LuciEntry: A Modular Lab-based Lucid Dreaming Induction Prototype

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Figure 1: LuciEntry, our modular lucid dreaming induction system. LuciEntry aims to induce lucid dreams by taking in brain and eye activity with electroencephalography (EEG) and electrooculography (EOG) sensors in the headband and classifying the sleep stage. At the appropriate sleep stage, various external stimuli, including visual, auditory, and electrical stimulation, are delivered to induce lucid dreams. If the user feels uncomfortable during the stimulation, they can press the emergency stop button to cease the ongoing stimuli.

ABSTRACT

Lucid dreaming is a state in which individuals become aware that they are dreaming, allowing dreamers to actively engage in controlling their dream content and transcending the limitations of the physical world. Lucid dreaming offers various mental and physical health benefits. However, current research combining multiple lucid dreaming induction techniques is often conducted with the researcher's intervention, lacking autonomy by relying on researchers to monitor the sleep stages and activating the devices manually. Recent studies also advocate for a modular system that can integrate multiple lucid dreaming induction techniques. We present LuciEntry, a prototype that includes a mobile app guiding the user through pre-sleep cognitive training and a system that assesses the user's sleep stage and triggers the external stimuli automatically to induce lucid dreams. We hope that this modular autonomous system will improve the research process, aiding in further research into lucid dreams.

CCS CONCEPTS

• **Human-centered computing → Interaction devices**.

KEYWORDS

Lucid dreaming; induction; interactive devices; modular; autonomous; prototype; system

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1 INTRODUCTION

Lucid dreaming is a unique state of consciousness where one is aware of dreaming whilst asleep [3]. In this state, dreamers can engage in volitional actions not limited by the constraints of the physical world, by being aware and able to control the contents of their dreams [8, 28]. There are many benefits to both mental and physical health when one experiences lucid dreams. For example, Lucid dreams can help one find creative inspiration, build their self-esteem, as well as their self-control [11, 18, 20]. Furthermore, researchers have also incorporated lucid dreaming into therapies to be used for treating various sleep disorders and other conditions [25].

However, lucid dreaming can be a challenging task to achieve and requires dedicated practice [26]. The techniques and processes to induce lucid dreams have been a topic of interest in the last decade and are still an active research topic that continues to this day, which includes multiple lucid dreaming induction techniques such as cognitive techniques, external stimulation and cortical stimulation [30]. Research involving the combination of techniques, particularly techniques involving external stimulations, would rely on researchers building a system to test the combinations of techniques and later on, during testing, monitor the user's sleep stage and trigger the stimuli manually. This process could prove challenging and taxing to researchers. Therefore, we designed LuciEntry, an autonomous modular system prototype for lucid dream induction. This system takes in a user's brain and eye signals, determines the sleep stage, and triggers stimulation through the use of interactive technologies at the appropriate sleep stage to induce lucid dreams autonomously. While the automation eases the process of lucid dream induction, the system also allows plug-and-play of the input and output components, which gives researchers the flexibility of component swapping. With the autonomy and modularity of our LuciEntry, lucid dream researchers can save 8 hours and their cognitive effort for every overnight study. They would no longer need to monitor participants manually, which also saves money that would otherwise be spent on hiring people to assist in conducting the studies. Furthermore, the lucid dream induction system has the potential to create new opportunities in the recreational and medical industries. This could lead to the development of jobs and markets focused on facilitating, curating, and distributing lucid dream experiences.

2 RELATED WORK

Lucid dreaming induction research has been a topic of interest since 1984 [7]. Lucid dreaming induction techniques are divided into four main techniques: cognitive techniques, external stimulation, substance intervention, and cortical stimulation [30].

Cognitive Techniques are the process of training the people's brains, priming it to a state ideal for lucid dreaming [8]. Some of these techniques include Mnemonic Induction of Lucid Dreaming (MILD), Reality Testing (RT) and dream diary [30]. The MILD technique requires people to wake up in the middle of the night, imagine a previous dream, convince themselves to remember the dream signs if dreaming again, go back to sleep and become lucid while falling asleep [22]. This induction technique has been applied before in multiple studies and shows an increase in the number of lucid dreams experienced by people [2, 8, 11, 22].

External stimulation describes techniques that condition the person to associate a specific sensory stimulus with dreaming awareness. Studies have covered auditory, visual, tactile and odour stimulation in an effort to induce Lucid Dreams [6, 9, 10, 19]. A study

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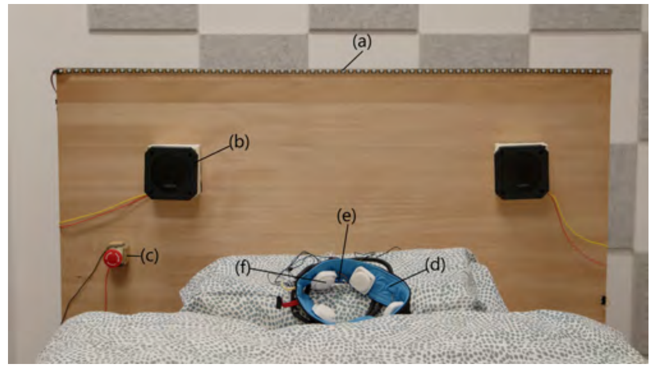

Figure 2: Our system includes a Raspberry Pi that runs our own developed server to process the user's brain and eye signals through (d) EEG electrodes and (e) EOG electrodes on the headset, and control the multiple external stimuli components, with (a) visual in the form of LEDs, (b) auditory in the form of speakers playing sound cues, and (f) electrical stimulation using tACS devices connected to electrodes on the headset. If the user feels uncomfortable because of the stimulations, they can press (c) the emergency button to stop the stimulations.

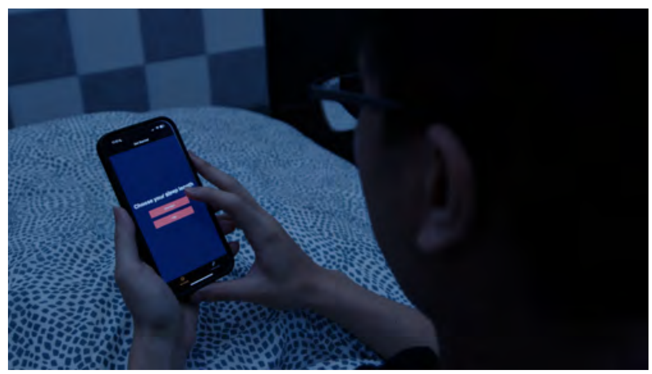

Figure 3: Our system is used in tandem with our own developed app that guides users through the pre-sleep cognitive technique MILD before their sleep.

by Carr et al. [6] utilised a combination of visual and auditory stimulation in an effort to have people practice a mental state of critical self-awareness to induce lucid dreams, which presented significant success in inducing lucid dreams. This combination of the external stimuli was proven to be successful in increasing the lucid dreaming frequency. However, it is unclear if the success is due to the effectiveness of specifically one of the external stimuli.

Cortical Stimulation is also a technique used to raise self-awareness in sleep to help induce Lucid Dreams by using electrical stimulation devices to deliver alternating currents at pre-determined frequency and intensity to people. Devices such as transcranial alternating current stimulation (tACS) devices would deliver such currents to people's scalps to induce lucid dreams. It is suggested that tACS could modulate cerebral oscillations and subsequently alter the pertinent cognitive processes [4].

Recent research studies on lucid dream induction have also begun combining multiple induction techniques together, yielding better results in inducing Lucid Dreams. For example, Carr et al. [6] combined cognitive training techniques with external stimuli (visual and auditory) to induce lucid dreams. This study was conducted in a lab setting during the mornings with morning naps, where researchers trained subjects with MILD before their nap, and during the subject's Rapid-Eye-Movement sleep, the researchers delivered the external stimulation to the subject manually [6]. With the implementation of the combined techniques, a 50 percent success rate was achieved in inducing lucid dreams in cued subjects.

With this knowledge of multiple different lucid dreaming induction techniques and the success when combining them, we aim to design an autonomous and modular system to further improve lucid dream induction research. To design such a system, we drew insight from HCI works such as Dormio, the first interactive sleep interface for priming people to think/dream of certain things during hypnagogia period [13], Dozer, a system that autonomously aids in sleep onset through auditory and electrical brain stimulation after detecting drowsiness in EEG [27], and Lucid Loop, a closed-loop lucid dream simulation VR experience [17]. These autonomous systems gave us insight into building a closed-loop system for automation. The system should be able to take in EEG and EOG signals from the user and deliver the external stimulations automatically. With the autonomy of the system, it would reduce the reliance on trained researchers or technicians to manually analyse and trigger stimuli, making it easier for researchers to conduct studies, particularly over the night or long periods of sleep.

We additionally drew insight from the Haptic-go-round system developed by Huang [14], which employs a plug-and-play format for their devices to be connected to the system, allowing them to choose the specific haptic devices they would like to employ at one time. Similarly, we aim to mimic this functionality for our system by employing a similar plug-and-play setup, allowing modularity for researchers to connect the external stimulation device they intend to test easily into the system and allowing researchers to test multiple combinations of techniques with ease.

3 LUCIENTRY

We present LuciEntry, designed as a modular, autonomous system to assist individuals in inducing lucid dreams. The system comprises a server running on a Raspberry Pi, a mobile application (Figure 3), a sleep tracker headset (Figure 2d), and multiple external stimulus devices (Figure 2a,b,f). The stimulus devices connect to the server via WIFI, and a new stimulus device can be integrated into the system with a simple registration process. Once deprecated, the device would no longer receive the commands from the server after unregistration. This modularity allows lucid dream researchers to effortlessly customize components for the desired combination of stimulations.

The stimulations provided include a 1 Hz LED flashing red light (Figure 2a), a theta binaural beat, a sound aiding in entering a meditation state [16], with white noise (Figure 2b), and a 40 Hz tACS (Figure 2f). The set of stimulations is inspired by Targeted Lucidity Reactivation [6] and Voss et al.'s tACS experiment [32]. Although

Voss et al.'s study results are questioned due to the lack of dream reports and the validation of lucidity through eye signalling [22], the usage of electrical stimulation remains an interesting direction for lucid dreaming induction research [3]. We thus still follow the protocol of 40 Hz tACS as a starting point, in an attempt to replicate and even improve the implementation of cortical stimulation into lucid dreaming.

Our mobile app introduces the concept of lucid dreaming and explains our system before sleep (Figure 3). The app also assists the user in performing wake-back-to-bed (WBTB) by setting alarms for both uninterrupted sleep and waking stage [12]. While using the phone before sleep might cause sleep disruption, potentially lengthening the time to fall asleep [15], sleep disruption is associated with higher lucid dream frequency [18]. Therefore, We speculate that the sleep disruption from the app may increase the lucid dream induction rate. However, we have added a voice-over to the app for the user who prefers less disruption. The app aims to guide the user through the pre-sleep stage automatically, using either visualization or verbalization.

During sleep, the user's brain and eye activity are monitored through the EEG and EOG sensors in the sleep tracker headset (Figure 2e). Our sleep tracker algorithm determines the user's sleep stage. When continuous Rapid Eye Movement (REM) sleep is detected, the system automatically delivers chosen external stimuli to increase the user's self-awareness during sleep, inducing a lucid state. The user signals lucidity by moving their eyes from left to right four times (LR signal [21]). The system ceases delivering the stimuli upon detecting the signal or if the user exits the REM state. The autonomy of the system reduces the time and effort required for lucid dream researchers to manually conduct studies.

Our system also features an emergency button (Figure 2c). If the user feels uncomfortable during the stimulations, they can press the button to disable the external stimulations (Figure 4).

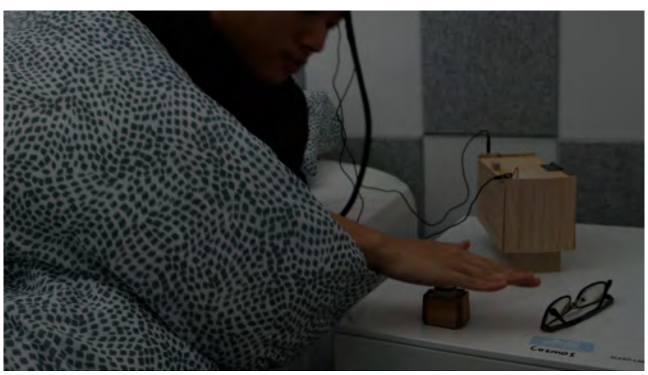

Figure 4: Our system includes an emergency stop feature in the event the user is uncomfortable or distressed to cease the ongoing stimuli.

4 PILOT STUDY

To understand the user experience of our prototype, we conducted three overnight pilot studies.

4.1 Participant

Three participants were recruited for our pilot study. One of the participants was a co-author, while the other two were recruited through word of mouth by the authors. All 3 participants are male, aged 22, 22, and 24. P1 is a regular lucid dreamer, P2 has no prior experience in lucid dreaming, and P3 has several times of lucid dream experiences, each lasting within a minute.

In consideration of potential negative effects associated with the usage of transcranial electrical stimulation in certain populations [1], exclusion criteria were implemented for the participants. The criteria include a history of brain surgery, head trauma, cognitive deficits, a history of tumors on the head, stroke, seizures, epilepsy or other intracranial diseases, implementation of intracranial metal, pregnancy, and repetitive migraines. No reimbursements were provided for participation.

4.2 Study Procedure

The study's procedures were approved by our institution's ethics committee. Participants came to the lab for an overnight sleep session between 10 pm and 8 am the next day. After informed consent was obtained, which included a pre-study questionnaire, participants were given a tour of the system in the sleep lab and instructed on how to use the system, including the mobile app, and how to correctly place the electrodes on their heads when wearing the sleep-tracker headband. We followed the MILD and Targeted Lucidity Reactivation (TLR) [6] protocols, where the participants were instructed to sleep for 4 hours with no external stimulation. After 4 hours, the participants are woken up by researchers and given the mobile app to use, which introduces them to lucid dreaming and recognises the cues of the system delivered through the external stimulus devices. During this time, the researcher would also help calibrate the intensity of the cues to the participant's desired level, ensuring they could comfortably notice the cues without being disturbed during sleep. The duration for the participant to be awake was around 30 minutes, including 10 minutes for cognitive training. After the training, the participants went back to sleep. When REM was detected, which in the system was detected by reading REM for more than 60 per cent of the time for the past 2 minutes, the external stimulations were delivered. The external stimuli include a 1 Hz LED flashing red light, a theta binaural beat with white noise and a 40 Hz tACS. The stimuli played for 10 seconds and were repeated every 20 seconds. The stimulation would be stopped if the LR signal is presented or if the participant is woken up. If the participant was woken up, they were asked to return to sleep until 4 hours had lapsed or they could not fall asleep anymore. After the sleep session, the participants underwent a semi-structured interview and filled out a post-study questionnaire to get insight into their experience and to obtain a dream report, if any. The participant was captured on camera during the whole study procedure period.

5 RESULTS AND DISCUSSIONS

Throughout the study, we encountered challenges in verifying the lucidity objectively, i.e., checking LR signals, due to erroneous EOG sensor data. Despite this limitation, two participants (P1 and P2) reported awareness of being in a dream during the activation of the stimulations, which exceeds the majority of lucid dream induction studies reviewed by Stumbrys et al. [29]. This indicates promising results for our system's functionality for lucid dream induction. The preliminary finding also validates prior work [6, 32], which explores the combination of different techniques and external stimulations for lucid dream induction. However, it is noteworthy that our study includes a small sample size, and participants' lucid dreams were of short duration. This suggests the need for a formal study with a larger participant pool, and we should also address methods to extend the lucid dream duration.

While the goal was to achieve autonomous lucid dream induction, two issues arose during the study. First, we noticed that the guidance provided by the mobile app was insufficient for the participants, requiring additional assistance from researchers in setting up the system and performing cognitive training. Second, version inconsistency in our scripts hindered the automatic delivery of stimuli to P2 and P3. Researchers had to manually run the scripts to trigger the stimulations when the REM stages were detected by the system for these participants. These issues highlight the importance of refining both the mobile app and the system design to enhance autonomy.

An interesting observation was the incorporation of pre-sleep experiences or external stimuli during sleep into the dream content for all of the participants. P1 watched car racing 1 hour before the study. During the study, he dreamt of driving a car in the same car racing field. He then saw the red flashing light (because of the activation of visual stimulation) from the brake lights of the car in front of him, which made him aware that he was in a dream. P2 dreamt of catching up with friends, potentially because he chatted with the researcher for a long time before the study. When the stimulation was activated, he was then immersed in an ocean-based environment. He reported that he dreamt of the ocean environment because of the theta binaural beats (the theta binaural beats sound like an ocean wave to him) so he realized he was in the dream. P3 reported that he was in a house where nobody liked him, which is related to the book, *Pride and Prejudice*, he read before the study. The finding of dream incorporation aligns with Carr et al.'s dream engineering [5] and underscores the potential of a dream interface.

However, the tightness of the sleep tracker headband impacted the wearability of our system. Prioritising comfort and designing various headband sizes could enhance the overall user experience, as suggested by Semertzidis et al. [27].

Moreover, participants' concerns about electrical stimulation were eased by the presence of an emergency button. P1 and P3 reported their concerns about using electrical stimulation on their heads. Although participants were informed that the study is ethics-approved and their safety would be ensured by the researchers, they still were afraid of the electrical stimulation, which might come from the lack of knowledge of how the system works [24]. However, after being informed that the emergency button would cease all the stimulation immediately, P1 and P3's worries about the electrical stimulation were relieved. Despite no actual use of the emergency button during the studies, its existence enhanced the credibility of the system and alleviated participants' concerns. We recommend incorporating a kill switch in the design of sleep devices with external stimulation to address user's concerns and ensure their safety.

6 LIMITATION, AND FUTURE WORK

There are several limitations to this work, and we propose potential avenues for addressing these in future work. First, due to technical issues, we were unable to collect LR signals for objective verification of lucidity, relying solely on dream reports. We will address the issues before conducting a formal study for future submission. Moreover, Jennifer Windt suggests that the dream reports are trustworthy if the reports are collected under ideal conditions, e.g., collecting the dream report as soon as the participants wake up from their dreams. However, to minimize the sleep disruption, we only collected the dream reports during the post-study interview. To address this, future iterations can incorporate a voice-recording feature into the system, allowing participants to report their dreams directly to the system upon waking. This would minimize sleep disruption while still providing reliable dream reports.

The short duration of lucid dreams observed in our study suggests a need for techniques to extend lucidity. Researchers could explore the implementation of lucid dream stabilization techniques, such as self-spinning, finger touching, and mediation [31], with interactive technology to prolong lucid dream experiences. Additionally, there is potential for developing a dream interface with dream incorporation. Lucid dreamer researchers can further use dream incorporation to facilitate lucid dreamers to set up a predetermined lucid dream environment, reducing lucid dreamers' effort for lucid dream content manipulation.

A future study with a larger sample size of 12 participants with a more diverse population is planned to further validate our system and understand the user experiences. Including a sham condition for comparison would provide insights into the system's efficacy. With the facilitation of our system, individual evaluations of each external stimulus and testing different combinations of stimuli could help identify key elements in lucid dream induction and enhance the overall success rate.

We acknowledge that our work has limited ecological validity [23] as we conducted our study in our research lab to ensure the system was working as intended, owing to the novelty of the design. To improve ecological validity, future work could design a portable version, allowing the user to induce lucid dreaming in the comfort of their own homes. This would also make lucid dreaming accessible, allowing more people to experience lucid dreams and profit from their many benefits.

7 CONCLUSION

With the modularity and autonomy of LuciEntry, we aim to alleviate the workload for researchers conducting sleep studies, enabling them to carry out more extensive investigations, including overnight studies. Furthermore, our autonomous system provides researchers with a streamlined approach to conduct lucid dreaming induction studies, offering ease of use and adaptability. The modularity of our system ensures that it can easily incorporate new lucid dream induction techniques, making it a future-proof solution.

The promising results obtained from the pilot study inspire confidence in the potential of our system. We envision that the system can contribute to and enhance ongoing lucid dream research. By providing a reliable and efficient platform for lucid dream induction, our system facilitates exploration into various applications and benefits of lucid dreams. Researchers can focus on advancing their understanding of lucid dreaming without concerns about the system used for induction, fostering a more robust and versatile landspace for future lucid dream research. Moreover, the lucid dream induction system potentially opens up new avenues in the recreational and medical industries, resulting in the emergence of job opportunities to distribute lucid dream experiences.

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