Lucid Loop: Exploring the Parallels between Immersive Experiences and Lucid Dreaming

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Figure 1: Lucid Loop uses a VR HMD and EEG Headband to experience and influence a lucid dreaming inspired 360 video.

ABSTRACT

Lucid dreaming is the awareness of being in a dream, allowing dream control and living out fantasies. It also has benefits for growth and well-being. Yet, lucid dreaming is not accessible to most people. So, we created Lucid Loop—a neurofeedback-augmented immersive experience that utilizes AI-enhanced visuals and spatial audio in a virtual reality device for simulating lucid dreaming. We interviewed nine lucid dreamers who tried Lucid Loop and helped us propose design considerations: dreaming allusions, reality checks, focus points with neurofeedback, people in the scene, and immersion. Lucid Loop was like lucid dreaming because of its capacity for emotionality and fluidity between self and environment. Participants also noted several differences where technology might be limited. Lucid Loop appears to accurately simulate lucid dreaming, with implications for enhancing well-being and future applications for lucid dream training. Our research generalizes to technologically-mediated simulations of other emotive or internal experiences.

CCS CONCEPTS

• **Information systems** → *Multimedia content creation*; • **Human-centered computing** → **Virtual reality**; *Empirical studies in interaction design.*

KEYWORDS

360 video, virtual reality, neurofeedback, lucid dreaming, deep dream, attention, eeg, creative AI

ACM Reference Format:
Alexandra Kitson, Reese Muntean, Steve DiPaola, and Bernhard E. Riecke. 2022. Lucid Loop: Exploring the Parallels between Immersive Experiences and Lucid Dreaming. In *Designing Interactive Systems Conference (DIS '22),*

DIS '22, June 13–17, 2022, Virtual Event, Australia

ACM ISBN 978-1-4503-9358-4/22/06…$15.00
https://doi.org/10.1145/3532106.3533538

June 13–17, 2022, Virtual Event, Australia. ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3532106.3533538

1 INTRODUCTION

Lucid dreaming, knowing one is dreaming while dreaming, can be the ultimate entertainment, but it is also a space to solve problems, be creative, rehearse situations, work through psychological issues, and have spiritual experiences [41, 66, 75]. Lucid dreaming is correlated with other positive benefits including increased positive mood after waking [73], and higher life satisfaction and self-esteem [34]. With all of these potential benefits, people could make use of this phenomenon to work through problems and difficult emotions or simply have a positive experience while dreaming. Imagine having the ability to control your dreams, for example, deciding to confront your nightmare instead of running away or waking up in terror. This is possible with lucid dreaming, but only accessible to those who can already lucid dream. Thus, we set out to study whether we could enable people to have an experience like lucid dreaming through a technologically-mediated simulation. We also wanted to better understand the potential and limitations of technology for simulating highly emotive and internal experiences like lucid dreaming, which could generalize to experiences and practices like awe, wonder, mindfulness meditation, up-regulation of joy and well-being, and body attention training.

Lucid dreaming is typically learned by rehearsing dreams and visualizing becoming lucid, and this technique—called Mnemonic Induction of Lucid Dreams or MILD—is an effective strategy for increasing lucid dreaming frequency [38, 45]. With the MILD technique, one concentrates on the intention to remember to recognize one is dreaming. This prospective memory technique can be done by imagining oneself becoming lucid in a dream and/or repeating a short mantra like "next time I'm dreaming, I'll remember I'm dreaming". While this technique for learning lucid dreaming seems simplistic, it is difficult to implement in practice. We need vigilance because we are working with subtle levels of consciousness and parts of the mind that are usually "quiet". Furthermore, this lucid dreaming technique relies on written and auditory guides that tell you to "imagine becoming lucid". This is a challenge because people have a hard time visualizing or practicing something they have never experienced before: recognizing they are in a dream and then changing the dream. Usually, when we practice a skill, we would learn by doing or watching others. However, with lucid dreaming we have limited opportunities to practice (i.e., only when we dream where we could only practice in the rare moments of becoming lucid), and we cannot directly observe others lucid dreaming. Ideally, we would have a way to lucid dream in our waking life to experience all its benefits. This is where immersive experiences, such as virtual reality (VR) and 360 videos, and neurofeedback might be beneficial in going beyond existing techniques by simulating key aspects of lucid dreaming.

1.1 Immersive Experiences

Lucid dreaming and immersive experiences have several parallels. First, in both cases, the self is immersed in a world that appears real yet at the same time is aware the world is a simulation. Second, what is experienced in the lucid dream or the immersive experience has real-world effects both on a psychological and behavioural level [79]. For example, one can change the outcome of a nightmare or practice a sport while lucid dreaming, and have that confidence carry over into waking life [30, 84]; training in VR is equally effective at enhancing performance compared to a non-simulated, control environment [30]. Third, both have emotional (i.e., perceptual cues to elicit emotion) and epistemic (i.e., cognitive cues to integrate and build knowledge) affordances [18]. Fourth, one can experience impossible or improbable situations either through lucid dream content or computer-generated immersive experiences. Carr et al. [12], Gonzalez-Franco and Lanier [23] point out that the mechanisms behind the illusory perception of VR echo that of dream generation; making VR an apt technology for facilitating both dream research and experience. Thus, given these parallels, there is an opportunity to explore immersive experiences as a means to simulate aspects of lucid dreaming in our waking life to receive its benefits for well-being.

1.2 Neurofeedback

Another critical component of lucid dreaming is practicing focused attention, such as seen in experienced meditators [74, 76, 85]. Research suggests that the focused attention component of mindfulness might increase lucid dreaming frequency [6] and prime positive lucid dream experiences [73]. One hypothesis is that when one attends to their environment more, then they are more likely to notice when they are dreaming (i.e., become lucid) and maintain focused attention to prolong lucidity.

One tool that may help with practicing focused attention is neurofeedback, a coaching and training technique that helps people learn how to change their neurological patterns to improve their mental and emotional state [19]. For example, the Muse is a multi-sensor headband that gives you real-time auditory neurofeedback of birds chirping when you are in a meditative state based on your brain wave activity. In simplified terms, most researchers consider there to be five main types of brain wave frequencies, each associated with a particular brain state: alpha, beta, delta, theta, gamma [56]. Early research employed neurofeedback of attention for lucid dreaming using alpha brain waves (input) and an intensity-modulated 250-Hz tone (output), and found it did not increase lucid dream frequency [52]. This is perhaps because current research shows that elevated brain wave activity of 40-Hz power (gamma brain waves), and not alpha, is associated with lucid dreaming [28, 49, 50, 83, 84] and focused attention [46, 82]. More recent studies have shown promising results using neurofeedback with sleep and dream staging [25, 68]. What if neurofeedback of focused attention, namely neurofeedback with gamma brain waves, can simulate aspects of lucid dreaming? What if we combined neurofeedback with an immersive experience? We wanted to explore these possibilities in this paper.

1.3 Objectives and Research Questions

The primary objective of this work is to explore the similarities and differences between lucid dreaming and a neurofeedback-augmented immersive experience designed to simulate aspects of lucid dreaming. This will allow us to better understand in what ways the features and mechanisms of immersive experiences parallel those of lucid dreaming, and where there are limitations. We present design

considerations for creating immersive experiences that support lucid dreaming by leveraging the unique features and mechanisms of immersive experiences. Our research contributes to the field of dream engineering, with implications not only for researchers to better study lucid dreaming but also for designers to technically develop neurofeedback-augmented virtual reality systems. We describe the design of Lucid Loop (Figure 1) and an interview study where we ask the following research questions:

(1) In what ways are lucid dreaming and immersive experiences, specifically Lucid Loop, alike and dissimilar?
(2) What are key design features and considerations for a technologically-mediated simulation of lucid dreaming?

2 RELATED WORK

We consider our research positioned at the intersection of four domains: neurofeedback, focused attention, immersive experiences, and lucid dreaming. The research at this intersection is still in its infancy, but growing—as evidenced by the emerging field of Dream Engineering in which this paper is situated [12].

2.1 Neurofeedback Systems

We are interested in focused attention neurofeedback because focused attention is closely associated with the practice of lucid dreaming. Most of the technological systems that use neurofeedback for focused attention were EEG-based.

MindFull used EEG neurofeedback on the focused attention facet of mindfulness. When the user was focused, they see feedback on a tablet. Results showed children were able to calm and focus their attention [2]. MeditAid also used EEG neurofeedback of focused attention, this time mapping alpha brain waves as the input with binaural beats (auditory illusions that occur when you hear different frequency sounds in different ears that some claim can increase your focus) as the output. Their findings suggested that aural feedback could add to distraction, as people strongly preferred quietness during meditation; haptic feedback might better support bodily awareness [62]. AttentivU was an EEG neurofeedback system integrated into wearable glasses to detect attentiveness and nudge the user with audio and haptic feedback [35]. A study with 48 adults showed AttentivU was able to redirect attention of participants back to the task at hand and improved their performance on a comprehension task compared to random and no feedback [35]. Finally, Sensorium was a multi-modal neurofeedback system that translated EEG brainwaves to sound and light. A study showed participants had increased bodily and mental awareness after experiencing Sensorium [27]. These studies show that neurofeedback of focused attention is feasible and effective.

As for the types of focused attention feedback that were most effective, Salehzadeh Niksirat et al. [61] developed a theory-grounded Attention-Regulation Framework for Neurofeedback that was validated through two experimental studies comparing their app *Pause* with an existing app *Headspace*. Their framework included three main design suggestions. First, relation response required repetition and slowness. Second, aligning with Attention Restoration Theory (ART), feedback should avoid tired cognitive patterns such as everyday environments or complex stimuli that stimulate judgement, and the feedback should be a minimal, soft stimulus where there is an anchor to promote effortless reflection. In Lucid Loop, we used EEG neurofeedback of focused attention together with minimal visual and auditory stimuli in keeping with the Attention-Regulation Framework for Neurofeedback.

2.2 Neurofeedback and Immersive Experiences

Immersive experiences and sensory stimulation technologies, such as VR and brain-computer interfaces (BCI), show great promise for furthering our understanding of dreams and how we could better support the experience of them [12]. PsychicVR used VR and EEG neurofeedback on the focused attention aspect of mindfulness meditation. When the user was focused, they were able to make changes in the virtual environment [1]. Similarly, RelaWorld used neurofeedback of concentration and relaxation in VR. Compared to a control condition (screen), participants had increased attention with both neurofeedback-augmented VR and VR-only [36]. SOLAR used breathing and EEG brainwaves to help novice meditators practice focused attention on breathing in VR. They followed four design principles: thought distancing, abstract visuals, reward system, and ART elements such as nature [57]. Finally, one study used gamma frontal asymmetry (which the researchers claim is associated with shifts in emotional state) neurofeedback with the Muse EEG headset in combination with 360 video in an HMD to coach attention back to a positive emotional state [80]. Here, the gamma asymmetry threshold was mapped to movement towards a waterfall; if the participant was below the gamma asymmetry threshold (more activity on the left side of the brain than the right), the screen freezes, a red filter appears, and a voice coaches the participant's attention back to a positive emotional state. Although not specifically designed for simulating lucid dreaming, all of these systems used neurofeedback of focused attention together with an immersive experience, which we used to draw inspiration for our own design.

2.3 Dreaming and Other Altered State Systems

There were a few systems that focused on dreaming and other altered states, though not all were neurofeedback-augmented immersive experiences nor were they directed at lucid dreaming. Yet, they helped explore how dreaming and other altered states could be visually and/or auditorily represented, which was important when designing our system for lucid dreaming. Inter-Dream was a novel multisensory interactive artistic experience driven by neurofeedback to help with restfulness and sleep-onset [68]. It used an HMD and projection as outputs. A mixed methods study found Inter-Dream significantly decreased pre-sleep cognitive arousal, negative emotion, and negative affect. Semertzidis et al. [68] suggested three design strategies: facilitate exploration, promote neurocentric agency, and facilitate self-expression. Dormio was a targeted dream incubation device that measured muscle control and brain waves (EEG) to detect sleep states and provided extended states of hypnagogia [25, 29]. In a controlled study, researchers found Dormio was able to successfully incubate the auditory prime "tree" in dreams in 67% of participants [29]. Hallucination Machine was a deep-dream neural network immersive 360 video system that simulated the visual hallucinatory experiences in a biologically plausible and ecologically valid way, as evidenced in two experiments [78]. Isness

was a multi-person VR journey where participants experienced the collective emergence, fluctuation, and dissipation of their bodies as energetic essence, comparable to a psychedelic experience. The design was grounded in six concepts from the literature: matter as energy, connectedness, unity, ego-dissolution, transcendence of space an time, and noetic quality [22]. One of the few neurofeedback systems designed to train for lucid dreaming states found that EEG alpha feedback together with audio and tones had no increase of lucid dreaming frequency [52]. These systems show some potential design possibilities for our system, Lucid Loop. However, we also wanted to incorporate the perspectives of actual, proficient lucid dreamers.

Kitson et al. [32] conducted a phenomenological study with proficient and active lucid dreamers and derived nine design considerations for immersive experiences: sensation and feelings of vividness and clarity; multisensory experience; exploration and sense of possibility; playfulness and childlike qualities; fantastical experiences such as flying; sense of control and agency; ease in and out of VR (seamless transitions); ceremony and rituals; abstract and nature elements. These design considerations have been utilized in several studies involving immersive experiences [33, 67, 68, 71]. Picard-Deland et al. [55] found that when participants experienced a flying VR game and then took a nap, they reported an increase in flying dreams, lucid control, and emotional intensity. This suggested a connection between what was experienced in VR could transfer over to lucid dreaming. This motivated us to create an immersive experience that simulates aspects of lucid dreaming by incorporating neurofeedback of focused attention and MILD techniques of lucid dreaming visualization. We used Kitson et al. [32] and Semertzidis et al. [68]'s design guidelines to form the basis of a lucid dreaming virtual experience and we were inspired by these previous works in creating an immersive experience with deep dream visuals and MILD techniques of "incubating" the lucid dream. We saw the unique opportunity to combine all of these concepts, which had not been done before, to determine how close the experience it affords was to actual lucid dreaming. The potential synergistic effects of combing techniques may lead to an experience like lucid dreaming in order for more people to experience lucid dreaming and all its benefits. We developed a technologically-mediated system and collected qualitative feedback from proficient lucid dreamers on its similarities and differences to lucid dreaming.

3 LUCID LOOP

3.1 Technical System

Lucid Loop is an immersive experience designed to simulate lucid dreaming through neurofeedback of brain waves associated with attention in the form of immersive visuals and audio (see our video figure for a demonstration). Lucid Loop here is the developed system that was first proposed as an early proof of concept prototype in the late-breaking work by Kitson et al. [31]. Participants wear a Muse 2 EEG headband and an Oculus Quest HMD, where sound emanates from the HMD's built-in speakers. While the accuracy of Muse 2 may be questionable compared to medical grade EEGs [63], we selected the Muse 2 because its ease of use and portability. Muse 2's dry electrode placement above the frontal region of the brain is optimally placed to detect brain waves associated with attention, and it can also sit comfortably underneath an HMD.

Muse 2 detects electrical brainwave frequencies that are correlated with certain cognitive states. The gamma (γ) frequency band ranges from 30-50Hz and is associated with hyperactive cognitive states compared to other frequency bands [56]. It is an oversimplification that specific brainwaves are associated with specific cognitive functions. The γ activity present in some brain regions may mean something different than γ in other regions. Rather, what we mean is that when considering the relative ratio of frequency amplitude in the frontal brain region in concert with that region's expected brain wave activity, we can infer participants are engaged in focused attention (neurocognitive process).

We aimed to provide neurofeedback on focused attention specifically, rather than a relaxed or meditative state. Most EEG neurofeedback systems use α or θ band frequencies, particularly in experiences that involve meditation. However, there is evidence that increased γ activity may be more related to meditation practices involving enhanced perceptual clarity and focused attention (see review: [42]). Lucid dreaming is also associated with higher γ activity over the frontal regions compared to baseline REM sleep [28, 50, 84], although Baird et al. [5] warns that this correlation could be an artifact of saccadic spike potential. Therefore, research indicates that γ frequency could be the most similar to a lucid state that we wanted our participants to experience.

Muse 2 is comprised of five frontal EEG electrodes including one baseline. Brain waves (μV) are read from EEG electrodes, where a Fast Fourier Transformation then computes the power spectral density of each frequency on each channel. We take the log of the sum of the power spectral density of EEG data over a frequency range (i.e., γ) to calculate the absolute power bands. The mean γ power levels of all EEG electrodes are then normalized to a score between 0 and 1. The score is 0 if <= 20th percentile of the distribution of band powers and 1 if >= 80th percentile.

We use an HMD, Oculus Quest, to enhance the immersive experiential qualities of lucid dreaming, which we predict will help with MILD technique. The Quest also allows the participant to look around naturally. *Hallucination Machine* used a 360 panoramic video with *Deep Dream*, which gave a more realistic simulation [78]; however, we chose a mixed 360 video and computer graphics approach to allow real-time modification of specific visual and auditory elements (described below), providing more flexibility for future iterations and control over experimental variables.

For the mapping, the higher the score, the greater the change in band power. Thus, if a participant is more in the γ frequency, this indicates that focused attention is also increased and the image and audio will become clearer. Likewise, when a participant is less in the γ frequency, then focused attention decreases and the image and audio will become more blurred (see Figure 2).

Taken altogether, electrical brain signals are read by the Muse 2 and sent to a third-party mobile app called Mind Monitor via Bluetooth. Mind Monitor relays the data to the Oculus Quest via OSC messaging over Wifi. The Unity program on the Quest takes the data and processes it into a score that is then mapped to the virtual visuals and audio. The visuals and audio are pre-processed so that they run on a loop but the layers of each video frame and the audio's volume vary with the change in electrical brain signal—a higher gamma brain wave signal associated with increased focused

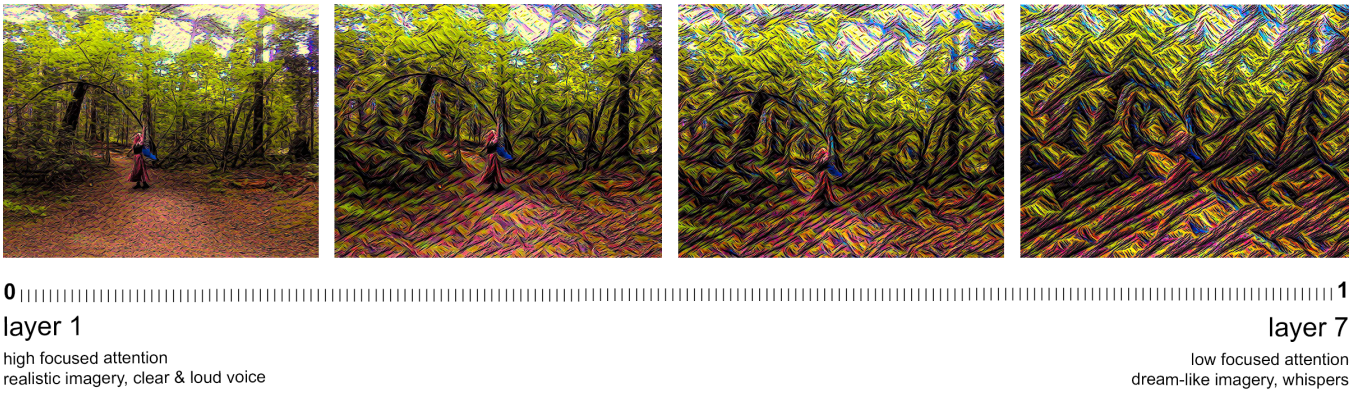

Figure 2: Four of seven deep dream layers with their corresponding brain waves score. Layer 1 = high focused attention, realistic imagery, clear and loud voice. Layer 7 = low focused attention, dream-like imagery, whispers.

attention would make the 360 video visuals clearer and the whispered MILD affirmation of "next time I'm dreaming, I'll remember I'm dreaming" louder. For more information on how the Unity code works, please see our online repository:

https://github.com/playfulbacon/Unity-Muse-Integration

3.2 Visual and Auditory Design

In Lucid Loop, we aimed for visual and auditory effects similar to lucid dreaming, where bizarreness is needed for the dawning of dreaming awareness, but once achieved, the lucid dream scene is relatively realistic [17]. We were inspired by research on the phenomenology of lucid dreaming for introspection and VR [32]. We also took design elements based on the recommendations from HCI researchers who did not look at lucid dreaming per se, but did look at focused attention or other altered states of consciousness (see Related Work). Given these prior works, we developed the following design elements of Lucid Loop (Table 1), which are depicted in Figure 3. While we based Lucid Loop on the most commonly reported elements of lucid dreams [32, 75], the nature of dreams is as vast as our experience of objective reality. Therefore, we did not expect all elements to exactly replicate our participants' own lucid dreaming experiences, but we were curious how these elements might or might not invite moments evocative of their lucid dreams.

Lucid Loop was created in a 3D game engine, Unity, with visuals artistically rendered with an enhanced Deep Dream AI system [15] together with Painterly [14]—a non-photorealistic rendering system that uses algorithmic, particle system and noise modules to generate artistic colour palettes, stroking and styles. By artistic, we mean the visuals are by themselves a piece of art, carefully crafted to feel similar to lucid dreaming experiences—bizarre, nature-inspired, abstract, and noetic. We tried 34 different visual styles in Painterly and selected a **Painterly Aesthetic** to create a sense of bizarreness and inaccuracy in the 360 real-world environment, reported by lucid dreamers in prior work (e.g., [47]). We ran the video frames through seven different times, each with increasing **Levels of Abstraction** in order to mimic the experience of perceptual clarity that arises when becoming lucid in a dream.

We included several points of focus for neurofeedback of attention: **Vivid Colours**, **Particles**, **Scarf Dancers**, and **Whispering**. The **Scarf Dancers** were also meant to represent dream characters that the user could project their own narratives onto, since interacting with dream characters is one the the most common lucid dreaming actions. **Affirmation** and **Looping** were MILD technique to better support lucidity. We chose the most common lucid dreaming affirmation "the next time I'm dreaming, I'll remember I'm dreaming"; this was recorded by a sound artist whom we told to simply speak the affirmation in a whispered voice. Finally, **Forest Environment** and **Non-Embodied Self** were both used as a means to support a non-ordinary experience. We chose brain waves as the main interaction because we wanted participants to focus on their attention and control the environment with their mind, which is the only interaction tool you have while lucid dreaming. The entire video loop was one minute long in order to give the user enough variation to stay interested during the 10-minute experience but also allow them to recognize the repeated patterns.

4 METHODS

We used a mixed methods convergent parallel approach. Quantitatively, we used Dream and Lucid Dream Frequency Questionnaire (LDFQ) [6] to screen for participants who were both active and proficient lucid dreamers; Mindful Attention Awareness Scale (MAAS) [10] to determine a participant's general tendency and ability to enter into a focused attention state. Qualitatively, with cued-recall debrief, we used semi-structured interviews while participants viewed a first-person recording of their session to help them remember their experience. We aimed to get a more detailed analysis of how participants interacted with and experienced Lucid Loop and better understand how participants believed the experience may or may not simulate lucid dreaming. We opted for cued-recall debrief [53] because it does not disrupt the experience itself, and it has been used in several HCI and Psychology studies of emotion [7, 11, 20, 59]. We screen recorded the immersive experience only, not the participant's physical body. The interviews lasted 15-30 minutes and consisted of 3-4 broad, open-ended questions (see supplementary material) as suggested by [21].

From a quantitative perspective, researchers are concerned with discovering facts about the phenomenon and they assume a fixed

Table 1: Lucid Loop Design Elements

Design Element	Description	Supporting References
Levels of Abstraction	seven visual layers, each with increasing abstraction of the environment that are mapped to neurofeedback	[32, 47, 57]
Painterly Aesthetic	visually plausible yet bizarre quality to prompt lucidity and support neurofeedback of attention	[61, 78]
Vivid Colours	bright and striking colours that can be a focus of attention	[32, 73]
Particles	matter as energy and more feedback on attentive state	[22, 57]
Forest Environment	surrounded by nature as a calm, yet non-everyday environment	[32, 57]
Scarf Dancers	sense of connectedness to others and bizarreness of situation to prompt lucidity	[22, 61]
Non-Embodied Self	having no body may result in feelings of ego dissolution	[22]
Affirmation	MILD whispered mantra on a loop of "next time I'm dreaming, I'll remember I'm dreaming"	[38, 45]
Whispering	auditory representation of thoughts as a way to support MILD technique	[57]
Looping	repetition of visuals and audio as a trigger for lucidity and supportive means for MILD technique	[61]

Figure 3: Screen shot of a participant's experience during Lucid Loop, showing the visual design including painterly aesthetic, vivid colours, particles, a scarf dancer, and a forest environment.

and measurable reality. However, the nature of experience, especially attention and user experience, is dynamic and a negotiated reality; this is much better suited to qualitative methods, which are more concerned with understanding human behaviour from the participant's perspective and does not assume a fixed reality [13]. It is very difficult to conduct research relating to felt experience for many reasons; most notably, felt experience is highly subjective. Most researchers believe the best way to study felt experience is through a combination of different measures in order to approach the construct from multiple perspectives and corroborate results [54]. Using qualitative methods to study felt experience, we intended to discover what kinds of sensations, feelings, and experiences participants had during Lucid Loop, as well as what they believed were the strengths and weaknesses of using both neurofeedback and immersive experiences to simulate lucid dreaming. We chose not to record brain wave signals from the EEG in order to focus on the felt experience and rich descriptions from participants. Anecdotally, we saw that gamma most reliably corresponded with focused attention compared to other bands.

4.1 Participants

We recruited 9 participants (4 Female and 5 Male), with a median age of 31 years (21-73 years range). The study was approved by the local ethics committee. Seven of our participants had lucid dreams at least once per month, and two had lucid dreams about 2-4 times per year. Glaser and Strauss [21] recommend the concept of saturation for achieving an appropriate sample size in qualitative studies, so we coded interviews at the same time the data was being collected until we found no new themes or information in the data. Dworkin [16] recommends the number of participants for in-depth interviews should be between 5-50. Malterud et al. [48]'s sample size guide for qualitative studies says higher information power considerations should determine sample size. Our study fits within the idea of higher information power, so requires a small number of participants. Finding participants with this special skill set was difficult, not to mention that recruitment occurred during the start of the COVID-19 pandemic. To recruit active and proficient lucid dreamers, we followed LaBerge [40] recommendation: verify that informants understand the concept of lucid dreaming by requiring the inclusion of a recognition phrase in a sample lucid dream report; use highly trained participants who are skillful and accurate observers of their conscious experiences. We posted online advertisements on social media groups (e.g., Facebook and Twitter) and lucid dreaming forums. Participants were naïve to this study and did not have prior relationships to us in order to decrease any power imbalances and increase the validity of their reports.

4.2 Screening Measures

4.2.1 Dream and Lucid Dream Frequency Questionnaire (LDFQ). Proficiency of lucid dreamers was assessed through the LDFQ [4, 6] based on [65]. LDFQ has high test–retest reliability for both Dream Recall Frequency (r = .85; p = .001; [65]) and Lucid Dream Frequency (r =.89; p = .001; [77]). See supplementary materials for more details. The **results** from the LDFQ to screen for participants determined that the median number of times participants remembered their dreams per week was 3.5 (*min = 1; max = 6.5)*, and the median frequency of lucid dreams per month was 2.5 (*min = .042; max = 8)*.

4.2.2 Mindful Attention Awareness Scale (MAAS). Developed by Brown and Ryan [10], MAAS is the most widely used mindfulness scale, with an internal consistency of .82, test-retest reliability of 0.81, and adequate convergent and discriminant validity. MAAS measures mindfulness as a trait that involves two components of consciousness: awareness and attention. See supplementary materials for more details. MAAS has one total score because the researchers believe mindfulness is comprised of many things that cannot be separated out into sub scales. Other scales integrate multiple facets of mindfulness that are not relevant to focused attention (e.g., FFMQ [3]) as it pertains to lucid dreaming, as reported to be a potential issue in Baird et al. [6]. Therefore, MAAS seems to be the most aligned measure to the construct we are interested in for this study, namely focused attention. The **results** of the MAAS in our study showed the median mindfulness score was 3.93 (min = 2.67; max = 4.73), indicating that the majority of participants were generally predisposed to a receptive state of mind in which attention, informed by a sensitive awareness of what is occurring in the present, simply observes what is taking place. But, this was not a strong disposition.

4.3 Procedure

The study took place in a university study space or, in one case, remotely from the participant's home. We created a 3m x 3m space dedicated to the immersive experience, so the participant could move around freely.

After obtaining informed consent, we asked participants to complete an online survey that included demographic information, the LDFQ, and the MAAS. Next, we explained the Lucid Loop experience to participants: the immersive visuals and audio will appear clearer when focused attention is high and will appear less clear when focused attention is low. We asked participants to play with their attention and notice how the experience responds. We also asked participants to be in the moment and simply experience Lucid Loop, since we would screen record their first-person experience and talk about it afterward. Participants were told that the experience would be 10 minutes, we would tell them when the time ended, and they could stop at any time without any consequence to the study. They could choose to remain seated or walk around for the experience; a virtual boundary would appear if they were near a wall.

When participants were ready to start the experience, we helped them put on the Muse 2 EEG headset, using the MindMonitor app to ensure all electrodes were connected and the signal was clear. Next, we helped participants fit the Oculus Quest VR headset on top of the Muse 2, being careful not to shift the electrodes. Using the Oculus Touch controllers, participants selected the "Record Video" option, which then began the Lucid Loop experience. We started the timer for 10 minutes, observed the participants, and helped them if needed. After 10 minutes, we helped participants take off the Oculus Quest and Muse 2, which automatically stopped the video recording and saved it to the device. For the semi-structured interview, we showed participants the video recording of what they just experienced on a laptop and we asked them to walk us through what they thought or felt. After the interview, participants were thanked for their time and to contact us if they had questions or additional insights from experiencing Lucid Loop.

4.4 Analysis

We used thematic analysis (TA) to analyze participants responses and explore what they thought and felt about Lucid Loop [9]. Two coders transcribed and coded the interview data in NVivo 12 Qualitative software. We used theoretical/deductive coding to get a more detailed analysis of how participants both interacted with and experienced Lucid Loop [54]. We had several passes through the data to generate codes. First, each coder separately went through two of the same interviews coding anything related to our research questions, namely mentions of the immersive experience, neurofeedback, and design features. This process was repeated for several rounds until the inter-rater reliability (Cohen's Kappa) was of good (.4 - .75) to excellent (> .75) agreement. Once agreement was met, the two coders coded all of the interviews again (agreement for each code = 80.44-100%). We finished with six higher level codes, each with several sub-codes: dreams, felt experiences, interaction, sounds, visuals, and wants. These codes and their sub-codes, along with their descriptions can be found in our supplementary materials.

We then looked for themes using strategies such as arranging key quotes in various ways and following the recommendations of Saldaña [60] and Soklaridis [70]. Finally, we went back to the original transcripts of the data to check whether our themes still made sense. We used member checking to ensure the validity of our account of participants' experience, and we compared participants' interview responses with their self-reported dream and lucid dreaming frequency and mindfulness scores to see if there were any potential connections.

5 RESULTS

We found three major themes from our thematic analysis: relating, discovering, and being there. *Relating* here means participants were connecting their experience with Lucid Loop to their own life experiences, which could be non-dreaming or lucid dreaming; elements in Lucid Loop would remind them of something they had experienced before or they recognized a specific person, place, or feeling. *Discovering* here means participants were figuring out the boundaries of Lucid Loop by playing with the interaction and testing the limits of the system. *Being there* means participants felt like they were an active observant in the experience, noting the feeling of physical presence of objects and people in the immersive experience while at the same time feeling like they were invisible to other actors in the immersive experience. While we discuss these themes separately, the data (quotes) can overlap two or all three themes.

Figure 4: Screenshots from the participant's experiences of Lucid Loop representing the different themes we found in our thematic analysis: relating, discovering, and being there.

5.1 Theme 1: Relating

Participants made connections between their own life experiences and their experience with Lucid Loop. They often commented "that reminded me of X" or used metaphors to describe their experience. The kinds of connections made were quite broad, including connections to art, people they knew, places they had been, altered states of consciousness and dreams they experienced, sounds that reminded them of something, and their own specific lucid dreaming experiences.

5.1.1 Relating to Art. While experiencing Lucid Loop, participants would often relate what they experienced to their own waking experiences. The patterns and aesthetic style reminded participants of specific art styles, such as Van Gogh for the brush-like style or Dali for the surrealism: "*It sort of reminded me of that animated Van Gogh movie where everything is pastel paint. I really liked that. It was just beautiful to look at.*" (P02) We used a post-impressionism style for the video, which Van Gogh is famous for. Thus, these responses seem to support our idea of using a Painterly Aesthetic with varying Levels of Abstraction in the design.

5.1.2 Relating to People and Places. The setting itself intrigued participants, and they would often try to figure out the people's identities and the forest's location. Several participants seemed to have a strong reaction to the male character in the scene, stating that they felt some recognition or had similar physical features to someone they knew: "*He kind of reminded me of a guru guy, like Ram Dass in his older years.*" (P03) For many, the physical surroundings were very familiar to the Pacific Northwest forests and hiking trails they had been to before. These responses seemed to support our design elements of using a Forest Environment and Scarf Dancers.

5.1.3 Relating to Altered States of Consciousness. The feeling of being in the virtual experience was likened to the movie *The Matrix* because "*how in VR everything is just a perception*" (P01). Similarly, participants likened their experience here to other altered states of consciousness, i.e., non-ordinary states, such as psychedelic trips and meditation:

> *It's kind of like a psychedelic experience where you go into a fear. If you go into a fear thought, it can spiral out of control and and it can be very hard to reel yourself*

> *back in. So I've learned even through that to recognize that this is just an experience, it's not going to last forever, it's just trying to show me something. And if I just surrender and relax everything will be ok.* (P03)

The Vivid Colours, Particles, Looping, and Non-Embodied Self were all design elements that seemed to be supported by these and other comments.

5.1.4 Relating to Sounds. For the MILD mantra, some participants found it creepy because the repetition felt like brainwashing. At the same time, the repetitive nature of the phrase *"next time I'm dreaming, I'll remember I'm dreaming"* was like participants' lucid dreaming practices of noticing when something feels weird and asking themselves if this is a dream. One participant wondered whether this MILD technique might help them have a lucid dream that night:

> *And as I was doing the experience and being in it, I kept hearing that. Well, first off, I'm not in a dream. But then I thought, I kept thinking, this is going to be so interesting like I'm so interested to see what's going to happen tonight. Will things be more vivid or what?* (P04).

The Affirmation itself seemed to be supported by our participants, but less so the Whispering.

5.1.5 Relating to Dreams. Often, participants (N=8) would compare Lucid Loop to their own dreaming experiences. In some instances, this comparison related to both the visual styles and clarity of Lucid Loop and both lucid and non-lucid dreams. For about half of the participants, they found aspects to be very much like their own dreaming experiences, with the aesthetic style evoking a more dream-like visual experience: "*The blurriness, the colour, and difficulties too to focus on things I found well done. I think it comes close to my experiences.*" (P07). Specifically, the fluidity of people and objects melding into one another, having people in the scene, and the nature elements were all reported to be like some participant's lucid dreams. The other half wanted Lucid Loop to look more realistic to better match their own dreaming experiences:

> *When I'm in a dream it looks like real life, it's more like me looking at you. But being in this experience, like I said, I feel like I'm in a cartoon. And when I'm in a lucid dream, I'd love to be in a cartoon actually, but it's never happened to me. So, I think it's too fantasy-like.* (P06)

We tried to make the virtual environment more ambiguous so that participants could insert their own narratives, yet it seems to have not worked with some because their own dreaming experiences were hyper-realistic. Perhaps virtual environments looking to imitate lucid dreaming could have more personalization options to fit the expectations of more people.

5.1.6 Relating to Lucid Dreaming. Participants (N=6) also made connections to their lucid dreaming experiences and their use of induction techniques such as reality checks. In Lucid Loop, they found they were unable to look to their hands to check their fingers, and they could not change or interact with the scene as they would in a lucid dream:

> *Being able to move to a different environment would be to me one thing that would be important because it's very characteristic of at least the lucid dreams I have... The idea of, for me, lucidity always involves moving somewhere else.* (P08)

While we wanted to focus on the interaction between mind and environment similar to lucid dreaming, it seems like participants wanted to have the perceived kinesthetic abilities of lucid dreaming too.

For some participants (N=7), the emotional feeling rather than the exact visuals and sounds were more important to lucid dreaming and Lucid Loop seemed to evoke an emotional response; even though this emotional response might be negative. For example, participants felt the experience was at times claustrophobic, dissociating, frustrating, or boring:

> *I have had dreams where there are spiralling patterns, but that was like a nightmare if I'm being honest. Which is actually what started my lucid dreams. I started having these sorts of experiences in a normal dream and thought well this isn't a pleasant experience so I'll just change it.* (P09)

While this participant voiced that it was an unpleasant experience, it did in fact reflect their actual lucid dreaming experience of controlling the visuals of a nightmare. Thus, their comments seem to support our design decisions.

Overall, all participants thought the experience was enjoyable, magical, beautiful, and mesmerizing: "*The very top shape looks like a flower and at the bottom near my feet was also like that, and I thought that shape, that flower shape, it's like mesmerizing, you could look at it for a long time.*" (P04)

5.2 Theme 2: Discovering

Participants discovered the boundaries, interactions, and limitations of the system by using specific techniques and observing how that changed the experience. They also noticed how the experience sometimes did not react in a way they anticipated or hoped for; sometimes questioning the accuracy of the equipment, the system, their own experience, and even their mental state.

5.2.1 Discovering Degree of Control. Many participants felt some degree of control over how they influenced the system, though many questioned their psychological state and whether that was accurately reflected in what they experienced. This was sometimes a question of the EEG's responsiveness: "*Maybe it takes training. Maybe I didn't plug into the means of influencing it properly. Maybe I should do something else. I think it requires more experimenting, like more than 10-15 minutes.*" (P07) A sense of control seemed to be tied closely with participants' sense of agency or feeling like they could act independently; the more barriers participants ran up against, the less agency they seemed to have.

5.2.2 Discovering Boundaries. When participants could not control the Lucid Loop experience or shift the visuals and sounds like they could in their own lucid dreams, they discovered the boundaries of the system:

> *I was confused at first, like I was trying to figure out what it's meant to be, if there is such a thing. You can*

> *completely distort it like you can in a lucid dream, but in a fixed environment. Like I thought you could change the colours of the objects, so I tried to do that for a while and I figured out that was not going to happen. So, I just moved my focus onwards.* (P09)

The neurofeedback seemed to work as participants expected, yet at the same time, participants wanted more interaction. It appeared that some participants did not yet have the attention regulation skills to change the virtual environment as they wished; and, since that was the only interaction of this experience, it felt limiting. We wonder if including more types of interactions, e.g., virtual touch, might enhance the experience rather than solely relying on brain wave interaction.

5.2.3 Discovering Interaction Techniques. Participants would play with different interaction techniques to see how they could influence the neurofeedback system using the EEG, but also to understand the limits of their agency over the system. These techniques included variations on mindfulness meditations, looking in certain directions, or focusing their attention on a specific object like the ground, sky, and trees. The general pattern, or visual aesthetic, was something participants focused on and they observed how the patterns changed with their attentive state:

> *I was going from a landscape that was pretty defined and then as I focused or concentrated, everything started zooming in onto the patterns and they got larger, louder, the voices were louder. And I thought that was cool because I actually tried to do that and got that feedback. So, that was really cool; it was very confirming like ok this is change in my mental state when I'm flexing this muscle. And then my intention was like how much can I flex? How much can I focus and concentrate?* (P02)

Mostly, though, participants looked at the moving elements of the scene, especially the people:

> *I feel like I just observed those thoughts and it took a while to focus on the dancer. And I feel like there was a part of me, especially when the dancer was really abstract, that was really inspired by the movements.* (P05)

Based on these comments, it seems like Vivid Colours, Particles, and Scarf Dancers all acted as points of focus as we intended.

5.2.4 Discovering Limitations. While participants felt Lucid Loop was, in general, a "cool" and "interesting" experience that they see the potential for simulating lucid dreaming, there were still some limitations. Participants felt they wanted to be able to interact with the space more by physically moving around, changing the scene, and talking with the characters. Specifically, in relating to their lucid dreams, the scene itself was a good start, but because participants could not move on to the next scene they felt stuck and the experience felt less like a lucid dream: "*I would say being able to move to a different environment would be to me one thing that would be important because it's very characteristic of at least the lucid dreams I have.*" (P08) Participants noticed that both the scenery elements and one of the virtual characters seemed to be hinting at the potential for moving down the virtual path. They expressed a desire to go down the path, even though eventually they discovered this was not possible:

> *I just wanted to go with him down the path. I think I stood up relatively soon after this because I wanted to try and follow him as opposed to thinking about following him in my head. I felt like I needed to stand up for some reason to try and go.* (P03)

In terms of design elements, the Forest Environment seemed to support the idea of a non-ordinary experience and was characteristic of participants' own lucid dreams. Including more non-ordinary environments would enhance the feeling that it is like a lucid dream.

5.3 Theme 3: "Being There"

Participants often commented on their sense of feeling like they were in the virtual environment, as well as relating to the feeling of being with other people and objects. For example, sensing the scale of the environment, wanting to reach out and touch virtual objects or people, and passively interacting with the virtual people. Participants felt they were physically there in Lucid Loop's virtual experience because of the visual and auditory immersive properties. Yet, they also psychologically knew they were simultaneously in two realities. We use the term "being there" instead of "presence" because the former term captures more of what participants described in their interview and the latter means something more specific in the VR literature [69].

5.3.1 Being There as Self. Participants expected the experience to feel more like their personal lucid dreams. Participants felt Lucid Loop was physically immersive and stimulating, yet they did not feel physically present because they could not see their body or hands to perform their usual reality checks: "*I thought you'd be able to see your hand. The thing is, for me in lucid dreams, my fingers are my means of what triggers I am in a dream. With that, I couldn't look at my hands and it didn't help.*" (P09) This sense of disembodiment was disorienting for some, while for others it was an interesting novelty that they wanted to explore more. One participant tried focusing on their body even though they could not physically see it. This seems to support our idea of a Non-Embodied Self, but that was not aligned with our participant's own lucid dreams. We suggest this could be another opportunity to have customization options to fit with a more personalized lucid dream experience.

5.3.2 Being There with Others. Participants also felt like the characters did not acknowledge their social presence as they usually would in lucid dreams. So, participants felt they were physically with the characters and nature elements, but it was more like they were ghosts witnessing an event take place with minimal influence: "*I was trying to touch them and I was like the invisible one there in that experience.*" (P01) It appears that our design element of including Scarf Dancers in the experience was aligned with participants' lucid dream experiences, but we needed to take that a step further in terms of interaction. It does not seem to be enough to simply have dream characters in the experience; there should be more interaction and acknowledgement of the user's existence in the virtual space.

5.3.3 Being There with Objects. Participants felt sensorily immersed in the virtual setting of Lucid Loop. That sense of being there with

different nature elements, such as trees and particles, helped support the feeling of perceived agency: "*I like the aspect that you're in the brush physically and that does something for your agency in the scene, which is ultimately what gets you to lucid dreaming.*" (P07) As P07 pointed out, a sense of agency and control is important for lucid dreaming, even if one chooses not to act and simply observes. It seemed like the trees especially helped support the feeling of being there because participants could look up and feel the scale of the environment, and the light shining through the trees also gave participants something to focus their attention on and was likened to a technique used to prolong lucidity:

> *If I looked up, it should be in the last two minutes, there should be a spot if I just looked at that it just brought the entire screen back into focus. Which, to be fair, is quite normal in lucid dreaming. If you look up, it does help.* (P09)

The Forest Environment seemed to support the feeling of being in the virtual environment, which is important for lucidity. The Vivid Colours also helped create a point of focus, as our design intended.

5.3.4 Being There with Sounds. In terms of the audio in Lucid Loop, participants felt that the repeating MILD Affirmation and the lack of any other sounds were not enough to support the feeling like they were in the dream scene. Instead, they suggested adding more nature sounds and sound effects in addition to the voice to enhance the feeling of being there:

> *They have like a scarf that they're moving something, like the sounds of how you move or sounds of how you walk along a trail, footsteps, and the wind, or birds. So, those audio will make it more real... not real, but hard to judge that I'm in a virtual reality.* (P01)

Therefore, the Affirmation itself was supporting the experience, and layering more sounds would only enhance the experience.

5.3.5 Being There as a Dream State. Some participants likened the experience to a dream state because they had an awareness that what they were seeing and hearing was not in fact ordinary reality and at the same time reacting to the environment as if it were "real":

> *So, it kind of resembled that state when I'm waking up in the morning. I know what's going on but I also know this is a dream. So, it kind of felt like that particular stage when you're about to get up in the morning and you're aware of your surroundings but you're still dreaming.* (P01)

One participant even went so far as to distinguish how Lucid Loop compared to both lucid and non-lucid dreams, namely the sensory immersiveness and awareness aspects:

> *It is immersive and you are experiencing something you wouldn't experience without it, but at the same time, you still know that you are awake, but you don't know you're awake when you're dreaming unless you're lucid. So, I think that's the distinction for me for what I've experienced here and what I experience when I'm actually dreaming, Because there isn't an awareness unless you become aware.* (P06)

The varying Levels of Abstraction was one aspect of Lucid Loop that contributed to this sense of non-ordinary reality. While they might not exactly match the visuals of a person's own dreams, these patterns and changing levels of abstraction were parallel to participants' recollection of visuals in their lucid dreams:

> *I think when I remember dreams in general but also my lucid dreams, the spatial and physical memories are very fluid, which is not like the real world. And having that fluidity, this captured that fluidity really well of people melding into patterns and other things.* (P02)

6 DISCUSSION

6.1 Comparison of Lucid Loop to Lucid Dreaming

We discuss the similarities, dissimilarities, and more nuanced results based on the interview responses from proficient lucid dreamers who tried Lucid Loop.

6.1.1 Similarities. One of the most prominent features similar to lucid dreaming was **focused attention**—an established technique to improve lucidity [74, 76, 85]. Lucid Loop was able to similarly support focused attention through the HMD's immersive qualities and ability to highly customize the environment with points of focus that were not distracting.

The second similarity to lucid dreaming was the concept of **fluidity**. This finding is congruent with ART, which states that complex stimuli, such as a room or urban space, can be too distracting and that soft stimuli are better suited to support effortless reflection [61]. Expert lucid dreamer participants reported that Lucid Loop and lucid dreaming both seem to support qualities of fluidity because of the less bounded nature of their realities.

The third similarity to lucid dreaming was in the feeling or the **emotional reaction** to the experience rather than the environmental richness. Dreaming experience has been linked to emotional processes [64], so having an emotional response in an immersive experience is perhaps similar to the functional role of dreaming in emotional processes. An EEG study showed that gamma activity is not only related to emotional processes and dream recall but it is also correlated to lucid dreams [83]. There seems to be some evidence that lucid dreaming is tied to emotional processing, and Lucid Loop here appears to afford unique qualities that support emotional experience. Therefore, both Lucid Loop and lucid dreaming appear to share the capacity for emotionality.

The fourth similarity to lucid dreaming was in the **techniques to maintain lucidity** such as reality checks. This finding was consistent with lucid dreaming guides that suggest spinning during a dream will prolong the lucid dream state compared to "just going with the flow" [39]. One participant even thought about spinning themselves, but decided against it because they did not want to fall over while wearing the HMD.

The fifth similarity to lucid dreaming was in **questioning reality**, i.e., practices of questioning whether you are in a dream or not [51]. For example, lucid dreamers are trained to look for peculiar events in their day-to-day life and, when one occurs, ask themselves if they are dreaming and maybe perform a reality check [81].

6.1.2 Differences. We found a few differences that could point to the current limitations of Lucid Loop for simulating lucid dreaming and offer suggestions for future improvements. First, almost all participants found personalized **reality checks** were lacking in Lucid Loop. Reality checks are what lucid dreamers usually do to confirm whether they are dreaming or not [41]. Something we could incorporate now to simulate the most common types of reality checks could be adding hand tracking and some semblance of a body, a time piece or text that changes oddly each time you look at it, and some flying-like locomotion.

The second difference was in the **people interaction**. Participants reported that they are the center of attention and people are looking at and interacting with them in lucid dreams. In Lucid Loop, the people are pre-recorded so they do not respond directly. Furthermore, in lucid dreams, participants are able to ask people questions and talk with them, but that is limited here. Two possible solutions could be to implement a multi-user immersive experience to have real-time interactions with others or make use of virtual agents that appear to react to the participant in a more natural way.

The third difference was the extent of the **multisensory experience**. In lucid dreams, some people (not all) will have a wide range of sensations such as haptics, smell, taste, and wetness, in addition to audio and visual components. Current immersive experiences simply can not recreate all senses to the extent we experience them in ordinary reality. However, we could include the latest immersive technology that at least tries to recreate some of the experiences of smell, haptics, taste, and temperature (e.g., [26]).

The fourth difference was in **controllability**. Most lucid dreamers could get to a point where they could do whatever they want and change whatever they want at any moment. In immersive experiences, this has to be programmed and it is very challenging to account for every possible interaction a participant may want. The closest possible solution is to utilize brain-computer interfaces (BCI) that might be able to differentiate between different brain states and change the immersive environment accordingly. Although BCI is increasingly used in HCI and artistic applications [58, 86], presently no such BCI exists that can directly read our thoughts.

6.1.3 Mixed. We found that there were mixed views on some aspects of Lucid Loop when comparing it to a lucid dream. Here, we find more subtleties when comparing lucid dreams and Lucid Loop. The first was in MILD technique's **lucid affirmations**, which are usually present or future tense statements that are designed to train thought patterns that will carry over from waking to dream state, e.g., I am fully aware of when I am dreaming. In Lucid Loop, the affirmation was a looping audio of "next time I'm dreaming, I'll remember I'm dreaming". However, participants were not voicing this affirmation themselves. Rather, the audio affirmation acted as a cue for which the participant may or may not engage with. It was unclear whether the benefits were in saying the affirmation yourself or if listening to the audio alone was sufficient. One recent study showed that the number one strategy for lucid dream control was verbal [43], which may or may not correlate with verbal affirmations in waking reality. One way to further explore this could be adding a microphone component so that participants can voice their own affirmation; and we might even record and replay that affirmation back to the participant for added personalization.

MILD's **dream visualizations** were the second component of Lucid Loop that had mixed comparisons to lucid dreaming. Lucid dreamers found the bizarreness of their dreams came from changes in ordinary perception rather than starting with a bizarre situation [32, 47]. The abstractness helped in supporting narrative and questioning reality, which was central to lucid dreaming practice. Simultaneously, participants felt too removed from ordinary reality. Perhaps the "trippiness" in lucid dreams comes from non-visual elements like movement or a feeling. We could incorporate aspects for movement or even flying, tone down the abstraction layers or have more subtle changes for specific parts of the experience, i.e., only certain elements in the scene change like the trees or the sky.

Nature elements, such as trees, were another aspect that some participants never dream, while others felt were very much like their lucid dreams, even if not a forest but an open field or a cave or mountains. We might try adding in more of these nature elements to round out the experience, though it is worth noting that too much stimuli in the scene could take away from the main intent [61], which was to practice focused attention.

The **lack of scene change** was also not quite like lucid dreaming. Participants found constrained movement to be most unlike lucid dreams where they can go as they please. One way to explore this idea in VR could be to slowly morph one scene into another like in an ambient video, e.g., [8].Participants could have some control of locomotion so they could explore more of the immersive space without being constrained to one place.

One final aspect of Lucid Loop that had mixed feedback was **agency**. The immersive properties of the experience helped to create some sense of agency or feeling of being there, yet at the same time, participants could not control the immersive environment to the same extent they would in a lucid dream. However, research suggests that dream control varies greatly amongst even proficient lucid dreamers [43]. Besides, neurofeedback is not explicitly about controlling your brain waves but rather noticing how they change. To give participants more control, we could add in more interactive elements like hand tracking, the ability to pick up some objects, and have the virtual characters respond more to the participant, e.g., the use of eye tracking to meet their gaze.

6.1.4 Summary. Given the above similarities and differences, we find that immersive experiences have several unique characteristics compared to lucid dreaming. Designers might leverage these characteristics to create immersive experiences that could help simulate the experience of lucid dreaming. First, immersive experiences can simulate a world that evokes the visceral experience of a realistic response. So, designers can simulate personalized situations of becoming lucid so that people can experience environments that are most like a lucid dream. Second, immersive experiences provide the opportunity for user interaction and feedback, especially when combined with bio- or neurofeedback. Designers can allow users to control and modify elements of the virtual environment, which is a key component of lucid dreaming. Finally, immersive experiences have a less bounded nature of reality much like dreams, where users can respond to one reality and at the same time be aware of another. Designers can leverage this capability of immersive experiences to help users question the nature of reality, and thus their dreams, and

Table 2: Lucid Loop Design Considerations from Results

Considerations	Application Examples	Design Elements
Allude to Experiences of Dreaming	Create a consciousness pathway of focusing	Differing levels of abstraction
	Create breaks in realism to trigger lucidity practices	Painterly aesthetic
	Personalize the experience through generic or ambiguous feedback	Forest environment
	Create a nature-inspired setting	
	Create a blurred and fluid aesthetic	
	Include noetic qualities that evoke emotion [44]	
Reality Checks	Create repeating video and audio	Looping
	Consider the absence of a body	Non-embodied Self
	Looking at your hands to check for anomalies via hand tracking [51]	
	Allow interactions not available in ordinary reality, e.g., virtual flying	
	Play with expectations of reality	
Points of Focus	Allow participants to find objects to anchor their attention, e.g., movement, contrasting colours, points of light	Forest Environment Vivid Colours
	Use limited focus points for novices since, in attention regulation practices, anything can become a focus point, which can be overwhelming [61]	Scarf Dancers Particles
People in the Scene	Include people and interactions with others	Scarf Dancers
	Create the virtual presence of others	

how they can change reality (literally but also perhaps their own perspectives on reality) simply by shifting their focused attention.

6.2 Design Considerations

In this study, we explored a comparison between Lucid Loop and lucid dreaming. In doing so, we identified features to design immersive experiences that promote focused attention (neurofeedback) and mnemonic induction (MILD), which are central components to lucid dreaming. In Table 2, we summarize the design considerations that we derived from our qualitative interviews and relate them back to our initial design elements of Lucid Loop listed in Table 1. We discuss considerations for designers and researchers looking to use consumer EEG neurofeedback of focused attention and HMD immersive experiences for simulating learning environments.

6.2.1 Neurofeedback of Gamma for Focused Attention. Prior work alluded to the significant role that γ brain waves play for both focused attention [46, 82] and lucid dreaming [28, 50, 84]. Based on this, we sought to determine whether γ waves might be feasible feedback for focused attention. Participants thought the visual and auditory elements reacted in an expected way, similar to their **focused attention** and **emotional reactions** in lucid dreams. Participants noted that seeing how they could influence the clarity of the images and audio was exciting in itself, and the constantly changing artistic visuals was a motivating factor in practicing focused attention because it gave them **agency** and made them **question reality**. These comments are highly promising for the potential for using γ brain waves as neurofeedback for focused attention. However, we are cautious in recommending it since there is still little evidence for its efficacy and much more research is needed to find a definitive answer [5]. Moreover, γ may be too simple a mapping to focused attention. In future iterations, we plan to look at γ in other brain regions as well as in relation to other frequency bands. We did find that participants who tried other techniques besides focused attention—such as open monitoring meditation, relaxation, and overthinking—were unsuccessful in trying to change the visuals and audio in the way they wanted. This suggests that focused attention may be a distinct state from related concepts such as mindfulness, relaxation, and anxious thinking.

6.2.2 Immersive Experiences as Simulated Learning Environments. Immersive experiences, especially those in HMDs that completely immerse your visual and auditory senses, were a crucial component in promoting mnemonic induction practices of lucid dreaming (MILD). Participants expressed that immersive experiences could be used as simulated learning environments to build skills around lucid dreaming practices such as MILD and focused attention. Immersive experiences have the ability to both invoke presence and simulate the fantastical features of dreaming that otherwise would not be possible, such as **interacting with certain people** you know, and **being in nature** or abstract worlds. Experiential learning theory suggests that immersive experiences might be able to support skills development (e.g., [37], but more research is needed to validate its efficacy in the context of lucid dreaming.

6.3 Limitations and Future Work

Future studies might test the effectiveness of Lucid Loop for enhancing well-being or increasing actual lucid dreaming through a more controlled setting where researchers can measure whether a participant has had a lucid dream through eye-tracking, a battery of validated questionnaires, and interviews. A recent paper that came out after the completion of this study shows preliminary evidence that synthetic dream-like environments can act as a training ground for more genuine critical questioning of one's reality [24]. Their results echo what we observed in our study with Lucid Loop, reinforcing the idea that immersive experiences might amplify lucid dreaming training during wakefulness.

While our study paves the way forward in better understanding the potential of the combination of neurofeedback and immersive experiences for simulating lucid dreaming, there are still many open questions on the effectiveness of Lucid Loop, and what these similarities mean for our understanding of reality.

In future work, we plan to explore the unintended consequences and ethical issues of neurofeedback-augmented immersive experiences. Dream Engineering is becoming increasingly prevalent, and the community has already faced potentially nefarious uses, including a beer company's use of targeted dream incubation to guide people toward dreaming about their product. The Dream Engineering community wrote an open letter with 35 signatories calling for proactive action and protective policies concerning the use of dream technology [72].

7 CONCLUSION

In this paper, we described the design and development of Lucid Loop—a system that provides real-time feedback on two central practices related to lucid dreaming, mnemonic induction and focused attention, in the form of a neurofeedback-augmented immersive experience. Reports from proficient lucid dreamers who tried the system felt there were many similarities between Lucid Loop and lucid dreaming. Based on the insights we collected from our users, we found three major themes that were important for designing a system for simulating lucid dreaming: relating, discovering, and being there. These results translated to six main design considerations: allude to experiences of dreaming, reality checks, points of focus, people in the scene, gamma as feedback for focused attention, and HMD immersive experiences. Based on our findings, it is feasible for neurofeedback-augmented immersive experiences to simulate aspects of lucid dreaming because of their close affinity to existing practices and the dreaming experience. With the impressive improvements in both immersive experiences and biosensing technology together with the insights gained from this and other research, it will become more and more feasible to fulfil our ultimate goal of providing lucid dreaming experiences with their benefits for well-being to a much wider audience.

8 ACKNOWLEDGEMENTS

We would like to thank Patrick Pennefather and Sheinagh Anderson for their contributions to the audio, Andy Bacon for the Unity-Muse integration system, and Alissa Antle for feedback on early paper drafts.

9 FUNDING SOURCES

This work was supported by the Social Sciences and Humanities Research Council of Canada [752-2018-2668].

REFERENCES

[1] Judith Amores, Xavier Benavides, and Pattie Maes. 2016. Psychicvr: Increasing mindfulness by using virtual reality and brain computer interfaces. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 2–2. https://doi.org/10.1145/2851581.2889442

[2] Alissa N. Antle, Leslie Chesick, and Elgin-Skye Mclaren. 2018-01-03. Opening up the Design Space of Neurofeedback Brain–Computer Interfaces for Children. 24, 6 (2018-01-03), 1–33. https://doi.org/10.1145/3131607

[3] Ruth A. Baer, Gregory T. Smith, Jaclyn Hopkins, Jennifer Krietemeyer, and Leslie Toney. 2006. Using Self-Report Assessment Methods to Explore Facets of Mindfulness. *Assessment* 13, 1 (March 2006), 27–45. https://doi.org/10.1177/1073191105283504

[4] Benjamin Baird, Anna Castelnovo, Olivia Gosseries, and Giulio Tononi. 2018. Frequent lucid dreaming associated with increased functional connectivity between frontopolar cortex and temporoparietal association areas. 8, 1 (2018), 17798. https://doi.org/10.1038/s41598-018-36190-w

[5] Benjamin Baird, Sergio A Mota-Rolim, and Martin Dresler. 2019. The cognitive neuroscience of lucid dreaming. *Neuroscience & Biobehavioral Reviews* 100 (2019), 305–323. https://doi.org/10.1016/j.neubiorev.2019.03.008

[6] Benjamin Baird, Brady A. Riedner, Melanie Boly, Richard J. Davidson, and Giulio Tononi. 2019. Increased lucid dream frequency in long-term meditators but not following mindfulness-based stress reduction training. 6, 1 (2019), 40–54. https://doi.org/10.1037/cns0000176

[7] Todd Bentley, Lorraine Johnston, and Karola von Baggo. 2005. Evaluation Using Cued-recall Debrief to Elicit Information About a User's Affective Experiences. In *Proceedings of the 17th Australia Conference on Computer-Human Interaction: Citizens Online: Considerations for Today and the Future (OZCHI '05)*. Computer-Human Interaction Special Interest Group (CHISIG) of Australia, Narrabundah, Australia, Australia, 1–10.

[8] Jim Bizzocchi. 2006. Ambient video. In *Proceedings of the 2006 ACM SIGCHI international conference on Advances in computer entertainment technology*. 45–es.

[9] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative research in psychology* 3, 2 (2006), 77–101. https://doi.org/10.1191/1478088706qp063oa

[10] Kirk Warren Brown and Richard M. Ryan. 2003. The benefits of being present: mindfulness and its role in psychological well-being. *Journal of personality and social psychology* 84, 4 (2003), 822. https://doi.org/10.1037/0022-3514.84.4.822

[11] Anders Bruun, Effie Lai-Chong Law, Matthias Heintz, and Poul Svante Eriksen. 2016. Asserting Real-Time Emotions Through Cued-Recall: Is It Valid?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction (NordiCHI '16)*. ACM, New York, NY, USA, 37:1–37:10. https://doi.org/10.1145/2971485.2971516

[12] Michelle Carr, Adam Haar, Judith Amores, Pedro Lopes, Guillermo Bernal, Tomás Vega, Oscar Rosello, Abhinandan Jain, and Pattie Maes. 2020. Dream engineering: Simulating worlds through sensory stimulation. *Consciousness and Cognition* 83 (2020), 102955. https://doi.org/10.1016/j.concog.2020.102955

[13] John W Creswell and Cheryl N Poth. 2016. *Qualitative inquiry and research design: Choosing among five approaches*. Sage publications.

[14] Steve DiPaola. 2017. Exploring the cognitive correlates of artistic practice using a parameterized non-photorealistic toolkit. *Leonardo* 50, 5 (2017), 531–452. https://www.muse.jhu.edu/article/670991

[15] Steve DiPaola, Liane Gabora, and Graeme McCaig. 2018. Informing artificial intelligence generative techniques using cognitive theories of human creativity. *Procedia computer science* 145 (2018), 158–168. https://doi.org/10.1016/j.procs.2018.11.024

[16] Shari L Dworkin. 2012. Sample size policy for qualitative studies using in-depth interviews. https://doi.org/10.1007/s10508-012-0016-6

[17] Jayne Gackenbach and Stephen LaBarge. 2012. *Conscious mind, sleeping brain: Perspectives on lucid dreaming*. Springer Science & Business Media.

[18] Andrea Gaggioli. 2015. Transformative Experience Design. In *Human Computer Confluence*. Sciendo Migration, 97–122.

[19] Andrea Gaggioli, Giuseppe Riva, Dorian Peters, and Rafael A. Calvo. 2017. Positive Technology, Computing, and Design: Shaping a Future in Which Technology Promotes Psychological Well-Being. In *Emotions and Affect in Human Factors and Human-Computer Interaction*. Elsevier, 477–502. http://linkinghub.elsevier.com/retrieve/pii/B9780128018514000185

[20] Yuan Gao, Nadia Bianchi-Berthouze, and Hongying Meng. 2012. What Does Touch Tell Us About Emotions in Touchscreen-Based Gameplay? *ACM Trans. Comput.-Hum. Interact.* 19, 4 (Dec. 2012), 31:1–31:30. https://doi.org/10.1145/2395131.2395138

[21] Barney Glaser and Anselm Strauss. 1967. Grounded theory: The discovery of grounded theory. *Sociology the journal of the British sociological association* 12, 1 (1967), 27–49.

[22] David R Glowacki, Mark D Wonnacott, Rachel Freire, Becca R Glowacki, Ella M Gale, James E Pike, Tiu de Haan, Mike Chatziapostolou, and Oussama Metatla. 2020. Isness: Using Multi-Person VR to Design Peak Mystical Type Experiences Comparable to Psychedelics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3313831.3376649

[23] Mar Gonzalez-Franco and Jaron Lanier. 2017. Model of illusions and virtual reality. *Frontiers in psychology* 8 (2017), 1125. https://doi.org/10.3389/fpsyg.2017.01125

[24] Jarrod Gott, Leonore Bovy, Emma Peters, Sofia Tzioridou, Stefano Meo, Çağatay Demirel, Mahdad Jafarzadeh Esfahani, Pedro Reis Oliveira, Thomas Houweling, Alessandro Orticoni, et al. 2021. Virtual reality training of lucid dreaming. *Philosophical Transactions of the Royal Society B* 376, 1817 (2021), 20190697. https://doi.org/10.1098/rstb.2019.0697

[25] Adam Haar Horowitz, Ishaan Grover, Pedro Reynolds-Cuéllar, Cynthia Breazeal, and Pattie Maes. 2018. Dormio: Interfacing with dreams. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–10. https:

//doi.org/10.1145/3170427.3188403
[26] Daniel Harley, Alexander Verni, Mackenzie Willis, Ashley Ng, Lucas Bozzo, and Ali Mazalek. 2018. Sensory vr: Smelling, touching, and eating virtual reality. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. 386–397. https://doi.org/10.1145/3173225.3173241
[27] Thilo Hinterberger. 2011. The sensorium: a multimodal neurofeedback environment. *Advances in Human-Computer Interaction* 2011 (2011). https://doi.org/10.1155/2011/724204
[28] Brigitte Holzinger, Stephen LaBerge, and Lynne Levitan. 2006. Psychophysiological correlates of lucid dreaming. 16, 2 (2006), 88. https://doi.org/10.1037/1053-0797.16.2.88
[29] Adam Haar Horowitz, Tony J Cunningham, Pattie Maes, and Robert Stickgold. 2020. Dormio: A targeted dream incubation device. *Consciousness and Cognition* 83 (2020), 102938. https://doi.org/10.1016/j.concog.2020.102938
[30] Alexandra D Kaplan, Jessica Cruit, Mica Endsley, Suzanne M Beers, Ben D Sawyer, and PA Hancock. 2021. The effects of virtual reality, augmented reality, and mixed reality as training enhancement methods: A meta-analysis. *Human factors* 63, 4 (2021), 706–726. https://doi.org/10.1177/0018720820904229
[31] Alexandra Kitson, Steve DiPaola, and Bernhard E Riecke. 2019. Lucid Loop: A Virtual Deep Learning Biofeedback System for Lucid Dreaming Practice. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–6. https://doi.org/10.1145/3290607.3312952
[32] Alexandra Kitson, Thecla Schiphorst, and Bernhard E. Riecke. 2018. Are You Dreaming?: A Phenomenological Study on Understanding Lucid Dreams As a Tool for Introspection in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA) *(CHI '18)*. ACM, 343:1–343:12. https://doi.org/10.1145/3173574.3173917
[33] Alexandra Kitson, Ekaterina R Stepanova, Ivan A Aguilar, Natasha Wainwright, and Bernhard E Riecke. 2020. Designing Mind (set) and Setting for Profound Emotional Experiences in Virtual Reality. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 655–668. https://doi.org/10.1145/3357236.3395560
[34] Karen Konkoly and Christopher T Burke. 2019. Can learning to lucid dream promote personal growth? *Dreaming* 29, 2 (2019), 113. https://doi.org/10.1037/drm0000101
[35] Nataliya Kosmyna and Pattie Maes. 2019. AttentivU: an EEG-based closed-loop biofeedback system for real-time monitoring and improvement of engagement for personalized learning. *Sensors* 19, 23 (2019), 5200. https://doi.org/10.3390/s19235200
[36] Ilkka Kosunen, Mikko Salminen, Simo Järvelä, Antti Ruonala, Niklas Ravaja, and Giulio Jacucci. 2016. RelaWorld: neuroadaptive and immersive virtual reality meditation system. In *Proceedings of the 21st International Conference on Intelligent User Interfaces*. 208–217. https://doi.org/10.1145/2856767.2856796
[37] Chongsan Kwon. 2019. Verification of the possibility and effectiveness of experiential learning using HMD-based immersive VR technologies. *Virtual Reality* 23, 1 (2019), 101–118. https://doi.org/10.1007/s10055-018-0364-1
[38] Stephen LaBerge. 1988. The Psychophysiology of Lucid Dreaming. (1988), 135–153. https://doi.org/10.1007/978-1-4757-0423-5_7
[39] Stephen LaBerge. 2009. *Lucid Dreaming: A Concise Guide to Awakening in Your Dreams and in Your Life*. Sounds True.
[40] Stephen LaBerge. 2014. Lucid dreaming: Paradoxes of dreaming consciousness. (2014). https://doi.org/10.1037/14258-006
[41] Stephen LaBerge and Howard Rheingold. 1990. *Exploring the world of lucid dreaming*. Ballantine Books New York.
[42] Darrin J Lee, Edwin Kulubya, Philippe Goldin, Amir Goodarzi, and Fady Girgis. 2018. Review of the neural oscillations underlying meditation. *Frontiers in neuroscience* 12 (2018), 178. https://doi.org/10.3389/fnins.2018.00178
[43] Alexandre Lemyre, Lidia Légaré-Bergeron, Roxanne B Landry, Donald Garon, and Annie Vallières. 2020. High-Level Control in Lucid Dreams. *Imagination, Cognition and Personality* (2020), 0276236620909544. https://doi.org/10.1177/0276236620909544
[44] Ross Levin and Tore Nielsen. 2009. Nightmares, bad dreams, and emotion dysregulation: A review and new neurocognitive model of dreaming. *Current Directions in psychological science* 18, 2 (2009), 84–88. https://doi.org/10.1111/j.1467-8721.2009.01614.x
[45] Lynne Levitan and Stephen LaBerge. 1994. Of the MILD technique & dream recall, of minds & dream machines. 6, 2 (1994), 9–12.
[46] Antoine Lutz, Lawrence L. Greischar, Nancy B. Rawlings, Matthieu Ricard, and Richard J. Davidson. 2004. Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. 101, 46 (2004), 16369–16373. https://doi.org/10.1073/pnas.0407401101
[47] Remington Mallett. 2020. Partial memory reinstatement while (lucid) dreaming to change the dream environment. *Consciousness and Cognition* 83 (2020), 102974. https://doi.org/10.1016/j.concog.2020.102974
[48] Kirsti Malterud, Volkert Dirk Siersma, and Ann Dorrit Guassora. 2016. Sample size in qualitative interview studies: guided by information power. *Qualitative health research* 26, 13 (2016), 1753–1760. https://doi.org/10.1177/1049732315617444
[49] Sérgio A Mota-Rolim, Daniel Erlacher, AB Tort, John F Araujo, and Sidarta Ribeiro. 2010. Different kinds of subjective experience during lucid dreaming may have different neural sub-strates. *Journal of Neuroscience* 25, 3 (2010), 550–7.
[50] Sérgio Arthuro Mota-Rolim, Andre Pantoja, Renato Pinheiro, Andressa Camilo, Tiago Barbosa, Igor Hazboun, John Fontenele Araujo, and Sidarta Ribeiro. 2008. Lucid dream: sleep electroencephalographic features and behavioral induction methods. In *First Congress IBRO/LARC of Neurosciences for Latin America, Caribbean and Iberian Peninsula. Búzios, Brazil*.
[51] Annabelle Neuhäusler, Michael Schredl, and Anja S Göritz. 2018. General knowledge about lucid dreaming and lucid dream induction techniques: an online study. *Int. J. Dream Res* 11 (2018), 179–185. https://doi.org/10.11588/ijodr.2018.2.50491
[52] Robert D. Ogilvie, Harry T. Hunt, Paul D. Tyson, Melodie L. Lucescu, and Daniel B. Jeakins. 1982. Lucid dreaming and alpha activity: A preliminary report. 55, 3 (1982), 795–808. https://doi.org/10.2466/pms.1982.55.3.795
[53] Mary M. Omodei and Jim McLennan. 1994. Studying Complex Decision Making in Natural Settings: Using a Head-Mounted Video Camera to Study Competitive Orienteering. *Perceptual and Motor Skills* 79, 3_suppl (Dec. 1994), 1411–1425. https://doi.org/10.2466/pms.1994.79.3f.1411
[54] Michael Quinn Patton. 1990. *Qualitative evaluation and research methods*. SAGE Publications, inc.
[55] Claudia Picard-Deland, Maude Pastor, Elizaveta Solomonova, Tyna Paquette, and Tore Nielsen. 2020. Flying dreams stimulated by an immersive virtual reality task. *Consciousness and Cognition* 83 (2020), 102958. https://doi.org/10.1016/j.concog.2020.102958
[56] Robert F Potter and Paul Bolls. 2012. *Psychophysiological measurement and meaning: Cognitive and emotional processing of media*. Routledge.
[57] Mirjana Prpa, Karen Cochrane, and Bernhard E Riecke. 2015. Hacking Alternatives in 21 st Century: Designing a Bio-Responsive Virtual Environment for Stress Reduction. In *International Symposium on Pervasive Computing Paradigms for Mental Health*. Springer, 34–39. https://doi.org/10.1007/978-3-319-32270-4_4
[58] Mirjana Prpa and Philippe Pasquier. 2019. Brain-Computer Interfaces in Contemporary Art: A State. *Brain Art: Brain-Computer Interfaces for Artistic Expression* (2019), 65. https://doi.org/10.1007/978-3-030-14323-7_3
[59] Denise Quesnel, Ekaterina Stepanova, Ivan Aguilar, Patrick Pennefather, and Bernhard E. Riecke. 2018. Creating AWE: Artistic and scientific practices in research-based design for exploring a profound immersive installation. In *IEEE Games, Entertainment, & Media Techniques Conference (IEEE GEM)*. Galway, Ireland, 200–207. https://doi.org/10.1109/GEM.2018.8516463
[60] Johnny Saldaña. 2015. *The coding manual for qualitative researchers*. Sage.
[61] Kavous Salehzadeh Niksirat, Chaklam Silpasuwanchai, Mahmoud Mohamed Hussien Ahmed, Peng Cheng, and Xiangshi Ren. 2017. A framework for interactive mindfulness meditation using attention-regulation process. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2672–2684. https://doi.org/10.1145/3025453.3025914
[62] Corina Sas and Rohit Chopra. 2015. MeditAid: a wearable adaptive neurofeedback-based system for training mindfulness state. *Personal and Ubiquitous Computing* 19, 7 (2015), 1169–1182. https://doi.org/10.1007/s00779-015-0870-z
[63] Phattarapong Sawangjai, Supanida Hompoonsup, Pitshaporn Leelaarporn, Supavit Kongwudhikunakorn, and Theerawit Wilaiprasitporn. 2019. Consumer grade eeg measuring sensors as research tools: A review. *IEEE Sensors Journal* 20, 8 (2019), 3996–4024. https://doi.org/10.1109/JSEN.2019.2962874.
[64] Serena Scarpelli, Chiara Bartolacci, Aurora D'Atri, Maurizio Gorgoni, and Luigi De Gennaro. 2019. The functional role of dreaming in emotional processes. *Frontiers in psychology* 10 (2019), 459. https://doi.org/10.3389/fpsyg.2019.00459
[65] Michael Schredl and Daniel Erlacher. 2004. Lucid dreaming frequency and personality. *Personality and Individual Differences* 37, 7 (2004), 1463–1473. https://doi.org/10.1016/j.paid.2004.02.003
[66] Melanie Schädlich and Daniel Erlacher. 2012. Applications of lucid dreams: An online study. (2012), 134–138. https://doi.org/10.11588/ijodr.2012.2.9505
[67] Nathan Semertzidis, Michaela Scary, Josh Andres, Brahmi Dwivedi, Yutika Chandrashekhar Kulwe, Fabio Zambetta, and Florian Floyd Mueller. 2020. Neo-Noumena: Augmenting Emotion Communication. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13. https://doi.org/10.1145/3313831.3376599
[68] Nathan Arthur Semertzidis, Betty Sargeant, Justin Dwyer, Florian Floyd Mueller, and Fabio Zambetta. 2019. Towards Understanding the Design of Positive Presleep Through a Neurofeedback Artistic Experience. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3290605.3300804
[69] Mel Slater. 2003. A note on presence terminology. *Presence connect* 3, 3 (2003), 1–5.
[70] Sophie Soklaridis. 2009. The process of conducting qualitative grounded theory research for a doctoral thesis: Experiences and reflections. *The Qualitative Report* 14, 4 (2009), 719.
[71] Ekaterina R Stepanova, Denise Quesnel, and Bernhard E Riecke. 2019. Understanding AWE: Can a virtual journey, inspired by the Overview Effect, lead to an increased sense of interconnectedness? *Frontiers in Digital Humanities* 6 (2019), 9. https://doi.org/10.3389/fdigh.2019.00009
[72] Robert Stickgold, Antonio Zadra, Pattie Maes, and AJH Haar. 2021. Advertising in Dreams is Coming: Now What? *Dream Engineering* (7 6 2021). https://dxe.pubpub.

org/pub/dreamadvertising https://dxe.pubpub.org/pub/dreamadvertising.

[73] Abigail Stocks, Michelle Carr, Remington Mallett, Karen Konkoly, Alisha Hicks, Megan Crawford, Michael Schredl, and Ceri Bradshaw. 2020. Dream lucidity is associated with positive waking mood. *Consciousness and Cognition* 83 (2020), 102971. https://doi.org/10.1016/j.concog.2020.102971

[74] Tadas Stumbrys and Daniel Erlacher. 2017. Mindfulness and Lucid Dream Frequency Predicts the Ability to Control Lucid Dreams. 36, 3 (2017), 229–239. https://doi.org/10.1177/0276236616683388

[75] Tadas Stumbrys, Daniel Erlacher, Miriam Johnson, and Michael Schredl. 2014. The Phenomenology of Lucid Dreaming: An Online Survey. 127, 2 (2014), 191. https://doi.org/10.5406/amerjpsyc.127.2.0191

[76] Tadas Stumbrys, Daniel Erlacher, and Peter Malinowski. 2015. Meta-Awareness During Day and Night: The Relationship Between Mindfulness and Lucid Dreaming. 34, 4 (2015), 415–433. https://doi.org/10.1177/0276236615572594

[77] Tadas Stumbrys, Daniel Erlacher, and Michael Schredl. 2013. Reliability and stability of lucid dream and nightmare frequency scales. *International Journal of Dream Research* 6, 2 (2013), 123–126. https://doi.org/10.11588/ijodr.2013.2.11137

[78] Keisuke Suzuki, Warrick Roseboom, David J Schwartzman, and Anil K Seth. 2017. A deep-dream virtual reality platform for studying altered perceptual phenomenology. *Scientific reports* 7, 1 (2017), 1–11. https://doi.org/10.1038/s41598-017-16316-2

[79] Isaac Y Taitz. 2014. Clinical applications of lucid dreaming therapy. *Lucid Dreaming New Perspect. Conscious. Sleep 2 Vol. New Perspect. Conscious. Sleep* (2014), 167.

[80] Jeff Tarrant and Hannah Cope. 2018. Combining frontal gamma asymmetry neurofeedback with virtual reality: A proof of concept case study. *NeuroRegulation* 5, 2 (2018), 57–57. https://doi.org/10.15540/nr.5.2.57

[81] Paul Tholey. 1983. Techniques for inducing and manipulating lucid dreams. *Perceptual and Motor Skills* 57, 1 (1983), 79–90. https://doi.org/10.2466/pms.1983.57.1.79

[82] Fred Travis and Jonathan Shear. 2010. Focused attention, open monitoring and automatic self-transcending: categories to organize meditations from Vedic, Buddhist and Chinese traditions. 19, 4 (2010), 1110–1118. https://doi.org/10.1016/j.concog.2010.01.007

[83] Ursula Voss, Romain Holzmann, Allan Hobson, Walter Paulus, Judith Koppehele-Gossel, Ansgar Klimke, and Michael A Nitsche. 2014. Induction of self awareness in dreams through frontal low current stimulation of gamma activity. *Nature neuroscience* 17, 6 (2014), 810–812. https://doi.org/10.1038/nn.3719

[84] Ursula Voss, Romain Holzmann, Inka Tuin, and J. Allan Hobson. 2009. Lucid dreaming: a state of consciousness with features of both waking and non-lucid dreaming. 32, 9 (2009), 1191–1200. https://doi.org/10.1093/sleep/32.9.1191

[85] B. Alan Wallace and Brian Hodel. 2012. *Dreaming yourself awake: Lucid dreaming and Tibetan dream yoga for insight and transformation.* Shambhala Publications.

[86] Drishti Yadav, Shilpee Yadav, and Karan Veer. 2020. A comprehensive assessment of Brain Computer Interfaces: Recent trends and challenges. *Journal of Neuroscience Methods* (2020), 108918. https://doi.org/10.1016/j.jneumeth.2020.108918