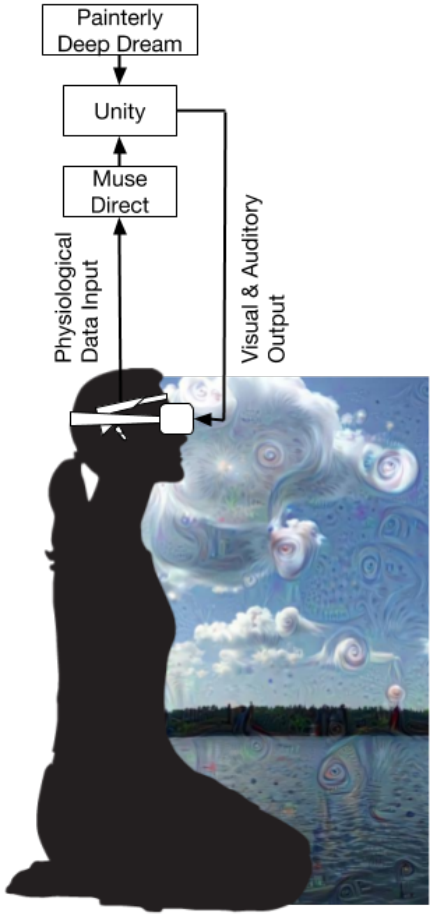

Figure 1: Lucid Loop system schematic. Painterly and *Deep Dream* creatively generate visuals to emulate dreams. The virtual environment becomes more lucid or "clear" when the participant's physiological signals indicate increased awareness.

Lucid Loop: A Virtual Deep Learning Biofeedback System for Lucid Dreaming Practice

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ABSTRACT

Lucid dreaming, knowing one is dreaming while dreaming, is an important tool for exploring consciousness and bringing awareness to different aspects of life. We present a proof-of-concept system called *Lucid Loop*: a virtual reality experience where one can practice lucid awareness via biofeedback. Visuals are creatively generated before your eyes using a deep learning Artificial Intelligence algorithm to emulate the unstable and ambiguous nature of dreams. The virtual environment becomes more lucid or "clear" when the participant's physiological signals, including brain waves, respiration, and heart rate, indicate focused attention. *Lucid Loop* enables the virtual embodied experience of practicing lucid dreaming where written descriptions fail. It offers a valuable and novel technique for simulating lucid dreaming without having to be asleep. Future developments will validate the system and evaluate its ability to improve lucidity within the system by detecting and adapting to a participants awareness.

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KEYWORDS

virtual reality; biofeedback; lucid dreaming; artificial intelligence; deep dream.

INTRODUCTION

Lucid dreaming is being aware one is dreaming while in a dream, allowing the dreamer to take control and do anything they want [14]. Lucid dreaming can be the ultimate entertainment, but is also a space to solve problems, be creative, rehearse situations, and work through psychological issues [21, 23]. Yet, learning to lucid dream takes time and practice, and not everyone is convinced by, nor successful with, traditional training methods that primarily use written and audio dream guides. *Lucid Loop* is a virtual reality (VR) experience that uses biofeedback from brain waves, heart rate, and respiration to help participants practice lucid dreaming awareness. Participants will receive artful visual feedback based on Deep Convolutional Neural Networks (DCNNs) in a VR head mounted display (HMD).

To the best of the authors' knowledge, this is the first VR experience that uses biofeedback to generate artistic representations of lucid dreaming practices. The main scientific contribution is twofold: improving our understanding of lucid dreaming awareness and creating a design of a new tool for simulating lucid dreaming without having to be asleep. We are developing this tool, which we will test and iteratively refine through both quantitative and qualitative measures. The goal is to have the VR experience directly respond to participants' physiological states of awareness that closely map to states of lucid dreaming awareness in order to gain its many benefits.

RELATED WORK

Deep Convolutional Neural Networks and Art

DCNNs are mainly used to classify images, objects, and faces [13], and their analysis requires innovative visualization methods. Google Researchers developed a novel visualization method called *Deep Dream*, whose goal is "to check what [the] network learned during training; [provide] a new way to remix visual concepts or perhaps even shed a little light on the roots of the creative process in general" [17]. This *Deep Dream* style essentially fuses the content from one image and the style from another into one novel image, resulting in an image with a dream-like quality (Figure 2). Researchers/Artists have begun to take advantage of this artistic quality to express visual creativity [5, 16].

Table 1: EEG Frequency Band Interpretation [19]

Band	Range	State
Gamma γ	30-50Hz	hyperactive
Beta β	13-30Hz	alertness
Alpha α	8-13Hz	relaxation
Theta θ	4-8Hz	meditative
Delta δ	0.5-4Hz	deep sleep

Virtual Reality and Biofeedback for Awareness

In the context of lucid dreaming, awareness is defined here as the explicit recognition of one's current experience. The goal of lucid dreaming and similar practices, such as meditation and yoga, is increasing awareness. In doing so, we can understand ourselves and the world around us on a deeper level [9]. Thus, the practice of lucid dreaming itself is beneficial because it provides us an opportunity to question reality and become more aware of our surroundings and internal physiological state.

One way to practice awareness of our physiological states is through biofeedback, a training technique to help people learn how to change their physiological response patterns to improve their

mental and emotional state [8]. Neurofeedback is a specific type of biofeedback where participants respond to a display of their own brainwaves; specific bands of brainwaves have been correlated with different physiological states (see Table 1). To enhance the experiential qualities of biofeedback, several researchers have added VR—review [11]. For example, *PsychicVR* maps concentration to levitation and increased virtual fire to promote mindfulness [2]. *Pulse Breath Water* is a VR experience with affect estimation in sound to promote relaxation, calm, engagement, and breath awareness [20]. We use biofeedback and VR for the same reasons previous researchers have, with the addition that other methods of learning lucid dreaming awareness can be inaccessible and challenging, e.g., written guides, or more expensive and carry higher risks, e.g., transcranial alternating current stimulation [25].

Technology Mediated Experiences of Altered States

Altered states of consciousness can provide people with powerful and sometimes life-altering experiences. Technology can support these experiences in a more accessible way than others, such as psychedelics and religious ceremonies. Moreover, technologies like VR can amplify immersion and realism beyond other media, thus enhancing the experience and potential positive outcomes. Yet, many technologically mediated experiences of altered states, especially lucid dreaming, lack empirical studies to back their claims. *SoundSelf* [3] and *V.DREAM* [1] are VR experiences that use psychedelic-inspired lights and sounds to try to induce trance-like states. *Somnai* is a guided lucid dreaming-inspired mixed reality experience with intricate multisensory stimuli [6].

There exist a few research-based designs. One such experience is *Hallucination Machine*, which uses DCNNs and panoramic videos of natural scenes, viewed immersively through an HMD. *Hallucination Machine* was shown to phenomenologically induce an experience similar to psychedelics, although the temporal distortion commonly associated with altered states was not evoked [24]. However, this system only allows passive viewing from one perspective and does not enable interactivity that would help participants reach this altered state naturally. Interactivity is important here since lucid dreaming requires the dreamer to actively move from non-lucid awareness to lucid, whereas psychedelics automatically provides hallucinations without active participation.

LUCID LOOP

Our aim is to simulate the visual and auditory aspects of lucid dreaming using *Deep Dream* to produce an embodied experience where participants may practice lucid dreaming awareness via biofeedback and VR. Visuals and sounds will become clearer, or more lucid, as participants' increase their awareness, similar to actual lucid dreaming [7].

In *Lucid Loop*, the participant wears a *Muse 2* EEG that also detects heart rate and respiration, and an HMD, e.g., Oculus Quest, while experiencing a short, looping virtual experience generated by the *Deep Dream* algorithm (see Figure 1). 3D spatialized audio will be presented through headphones to

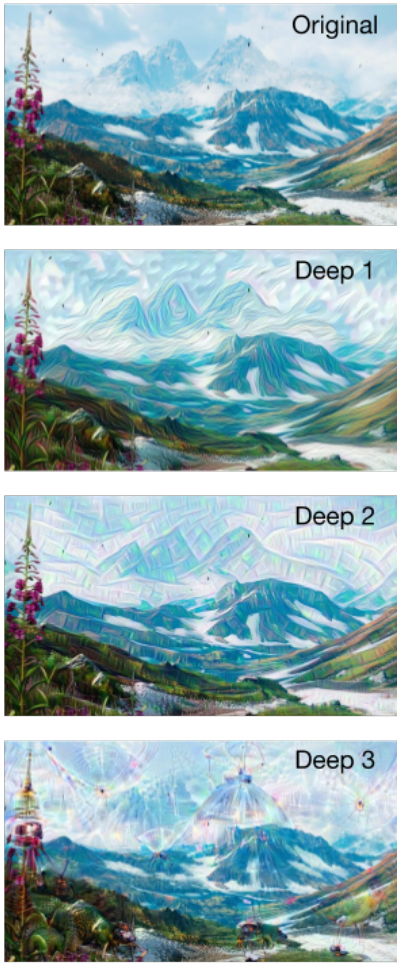

Figure 2: Unity scene (Asset Store: *Alpine Environment*) with *Deep Dream* (deepdreamgenerator.com) that makes different outputs depending on layer depth, from low (top) to high (bottom)

give the listener the impression of a realistic sound source within a 3D environment. *Muse 2* detects participant's brainwaves that are correlated with certain states (Table 1). In *Lucid Loop*, participants are given positive visual and auditory feedback about their awareness when their physiology changes similarly to what is observed for lucid dreaming. That is, visuals and sound increase in clarity when EEG β and γ band powers increase, α and θ band powers decrease, and heart and respiration rate increase; vice-versa when visuals and sounds decrease. Lucid dreaming studies show elevated levels of autonomic nervous system activity occurs 30sec before the onset of a lucid dream, as evidenced through respiration rate, heart rate, and skin potential [15]. EEG studies show increased β band power over parietal regions and γ in frontal regions during lucid compared to baseline REM sleep [10, 26].

We chose to use artistic representations of data as opposed to graphical or more simplistic representations for two main reasons: one because understanding raw data for the average person is not intuitive; two because we wanted the experience itself to be intrinsically rewarding even if one is unsuccessful in trying to change their physiological state.

VR Visual Design

We use an HMD with six degrees-of-freedom head-tracking to enhance the immersive experiential qualities of lucid dreaming and allow the participant to look around naturally. *Hallucination Machine* used 360 panoramic video with *Deep Dream*, which can give a more realistic simulation [24]; however, we chose a computer graphics approach to allow real-time modification of any element, providing more flexibility for future iterations and control over experimental variables. *Lucid Loop* will be created in Unity, with visuals modified using *Deep Dream* and Painterly—a non-photorealistic rendering system that uses algorithmic, particle system and noise modules to generate artistic colour palettes, stroking and styles [4]. In *Lucid Loop*, we aim for a visual effect similar to lucid dreaming awareness, where bizarreness is needed for the dawning of dreaming awareness, but once achieved, the lucid dream scene is relatively realistic [7]. We are inspired by research on the phenomenology of lucid dreaming for introspection and VR [12], which suggests the use of nature, abstraction, clarity, curiosity, and perceived autonomy for VR design. However, research on the phenomenological differences between lucid and nonlucid dreams show mixed results [7]. We plan to test these lucid dreaming components in future phenomenological experiments.

Lucid Loop will be an open, nature scene with other interactive elements that provoke curiosity. DCNN imagery will provide a level of abstraction needed for a dream-like effect, e.g., Figure 2. The image layers themselves will range from very abstract to completely clear, mimicking levels of clarity in lucid dreaming. We do not input physiological signals directly into the DCNN yet since we first aim for high quality, artistic content that changes in real-time, and current technology does not yet allow for this. Future iterations will have physiological signals generate deep dream content in real-time.

Research Design and Implementation

This research will be conducted in two phases: validating the system components; conducting more extensive testing and an evaluation of the system's ability to increase lucid dreaming awareness.

Phase 1: Test and Validate Components. First, we will measure physiological signals from brain waves, heart rate, and respiration to validate participants' experience of lucid awareness. We will collect data from participants wearing *Muse 2* with a VR HMD over top. We will measure a baseline EEG reading using the Klimesch Technique, where we measure each band during two minutes of eyes open and one minute of eyes closed [22]. This provides a measure of individual frequency for each band. We will collect and record data with Muse Direct, a visualization and recording tool for *Muse 2*.

Phase 2: Evaluation of System. We will use a mixed methods approach by triangulating data to evaluate *Lucid Loop*. Physiologically, we will measure outputs from brain waves, heart rate, and respiration. We will look at self-reported responses from both validated questionnaires and semi-structured interviews based on cued-recall debrief—a method that allows the participant to fully experience the system without disturption and avoids memory bias by showing the participant a first-person perspective recording of their experience [18].

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Biofeedback Mapping

The participant experiences real-time biofeedback in the form of creative visuals and audio that are mapped to data from *Muse 2*, a wearable headband comprised of five frontal EEG electrodes including one baseline; one photoplethysmogram (PPG); one gyroscope; one accelerometer. Heart rate is calculated from PPG, and respiration from a combination of PPG and gyroscope. Brain waves (uV) 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, β, α, θ, and δ) to calculate the absolute power bands. The mean γ, β and θ 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. The higher the score, the greater the change in band power. Thus, if a participant increases their γ, β and θ scores, this indicates that lucidity is also increased and the image and audio will become clearer. Likewise, when γ, β and θ scores decrease, then lucidity decreases and the image and audio will become more abstract. Increased heart rate and respiration will also contribute to a clearer or more lucid image, but to a lesser extent since these physiological responses are innervated by both sympathetic and parasympathetic nervous systems so the meaning of their responses is less evident.

CONCLUSIONS AND IMPLICATIONS

We propose a novel VR deep learning biofeedback system for lucid dreaming awareness. Components of *Lucid Loop* have already been developed, but the combination of them is what makes this system unique. Moreover, an embodied experience of practicing lucid dreaming awareness without having to actually be asleep is also new. *Lucid Loop* has the potential to provide a powerful new tool to complement the increased interest of research into lucid dreaming and its practices, whose benefits contribute to well-being. *Lucid Loop* uses direct feedback to playfully support awareness of one's state, ultimately helping to self-regulate one's state and enable more frequent or sustained lucid dreams.

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