Dreamware: A Brain-Computer-Interfaced Multisensory Capsule Room for Dream Engineering

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Abstract

Dream engineering is an emerging field within Human-Computer Interaction (HCI) that uses interactive systems to monitor sleep stages and deliver sensory stimuli to influence dream content for human well-being. Existing systems face two key limitations: 1) for sensing, the absence of deployable systems with laboratory-grade sleep staging capability creates a barrier to translating dream science into everyday contexts, and 2) for stimulation, reliance on single or limited sensory modalities fails to approximate the multimodal nature of naturalistic dreams. We present Dreamware, a brain-computer-interfaced multisensory capsule room addressing both limitations. The system integrates a hydrogel-based, flexible EEG wearable with a high-accuracy sleep-staging algorithm targeting N1 and REM sleep. Dreamware delivers synchronized, closed-loop stimulation across five sensory modalities: auditory, olfactory, visual, somatosensory, and thermoceptive. This work presents the first out-of-the-lab dream engineering system to achieve laboratory-comparable sleep staging alongside coordinated multimodal stimulation, advancing dreaming as a programmable design space for HCI.

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CCS Concepts

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

Keywords

Brain-Computer Interfaces, Dream, Sleep, Wearables

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1 Introduction

Across millennia and cultures, dreams have long been a subject of fascination and inquiry. From ancient Egyptian hieroglyphs depicting divine messages to Freud's explorations of the unconscious mind, dreams bridge reality and imagination, inspiring scientists to understand these phenomena's underlying mechanisms and benefits. Contemporary neuroscience research has revealed that dreams are related to critical functions for cognitive and emotional well-being, showing their influence in memory consolidation [11, 24, 43], emotional regulation [5, 34], and creative problem solving [29]. While the sleeping brain filters out most environmental input, it retains a limited capacity to process and integrate select sensory stimuli, a phenomenon wherein real-world cues occasionally cross over into dream content. This aligns with enactivist perspectives in cognitive science, which hold that cognition arises from dynamic interactions among mind, body, and environment. From this view, sensory stimuli such as sounds or scents may serve not merely as passive inputs but as structuring elements that shape the unfolding of dream cognition [45, 46]. Thus, an opportunity arises to influence dream experiences through carefully timed sensory input.

Grounded in these sleep and dream science theories, dream engineering emerged as a burgeoning Human Computer Interaction (HCI) research field that combines neuroscience, psychology, and technology to intentionally influence, modify, or induce specific dream content and experiences through interactive systems [9, 38]. Previous explorations include wearable gloves used during the hypnagogic state with audio prompts for creativity enhancement [16, 18], olfactory wearables based on memory consolidation for language learning [2, 3], and wearable electroencephalography (EEG) based systems for inducing lucid dreaming [48, 49]. These technologies illustrate how dream engineering is transforming sleep from a passive state into an interactive space for enhancing memory, fostering creativity, and regulating emotion [17, 44, 51].

However, current interactive systems for dream engineering face two key limitations. First, regarding sensing, no existing system combines real-world deployability with laboratory-grade sleep staging capability, creating a barrier to translating dream science from controlled laboratory settings into everyday contexts. Second, regarding stimulation, most systems rely on a single or limited sensory modalities for dream intervention, constraining the richness of achievable dream engineering experiences.

In this paper, we present Dreamware, a brain-computer-interfaced multisensory capsule room addressing both limitations. Specifically, the system contributes a novel hydrogel-based EEG wearable and PSG-validated sleep staging algorithm, and integrates these with coordinated stimulation across five sensory modalities within a unified closed-loop architecture. The system integrates a hydrogel-based, flexible EEG wearable with a sleep staging algorithm trained on overnight polysomnography (PSG) data from 44 participants, achieving 92.23% accuracy (Cohen's κ = 0.84) for REM sleep classification and 63% accuracy (Cohen's κ = 0.615) for N1 sleep classification compared to gold-standard PSG scoring. Leveraging this precise sleep stage detection, Dreamware delivers synchronized, closed-loop stimulation across five sensory modalities (auditory, olfactory, visual, somatosensory, and thermoceptive) for targeted dream engineering.

This work contributes the first out-of-the-lab dream engineering system to achieve laboratory-comparable sleep staging alongside coordinated multimodal stimulation. By integrating multiple sensory channels within a unified adaptive architecture, we provide HCI researchers and designers with a holistic framework for developing sleep-based interactive experiences. This approach opens pathways for therapeutic applications, including nightmare intervention [31, 33], stress reduction [39, 47], and memory enhancement [21, 37]. Ultimately, we envision this work as a step toward realizing sleep as a programmable design space for HCI.

2 RELATED WORKS

2.1 Interactive Systems for Dream Engineering

Sleep is a complex physiological state comprising Non-Rapid Eye Movement (NREM) stages N1, N2, and N3, and Rapid Eye Movement (REM) sleep, each serving distinct functions [35]. Accurate detection of N1 and REM sleep is critical for dream engineering, as these stages represent distinct windows for intervention. N1, the transitional state between wakefulness and sleep, is characterized by a hypnagogic state with vivid imagery and heightened receptivity to external stimuli. Compared to N1, REM sleep produces narratively complex and emotionally intense dreams, marked by high cortical activation and hyperassociative cognition [20]. Precisely timed stimulation during these stages enables researchers to shape dream content through sensory input [9].

Interactive systems for dream engineering employ a range of sensory interfaces to transform sleep into an active, engineered experience. However, these systems typically rely on consumer-grade sensors or proxy physiological signals rather than validated sleep staging, and none have demonstrated accuracy comparable to gold standard PSG. Wearable systems such as Essence [2, 3] utilize an olfactory interface that varies the frequency and intensity of scent release based on biometric or contextual data, leveraging the olfactory system's direct pathways to the amygdala and hippocampus to modulate mood and memory consolidation. Using the Targeted Dream Incubation (TDI) technique, Dormio [16, 18] provides a hand-worn device employing flex sensors, heart rate monitoring, and electrodermal activity (EDA) to detect hypnagogic onset and deliver serial auditory prompts that direct the thematic content of dreams, with the aim of enhancing creativity. To induce lucid dreaming, LuciEntry [48] and LuciTouch [12] employ EEG and EOG sensing to measure real-time sleep stage and dreamer lucidity.

2.2 Dream Engineering Techniques

Building on the sleep staging described above, researchers have developed various protocols for influencing dream content through precisely timed interventions. These techniques differ in their target sleep stages, sensory modalities, and whether they require pre-sleep priming. Dream engineering techniques can be broadly categorized by their mechanisms and objectives (Table 1). Targeted TDI represents a direct approach to content manipulation, employing auditory cues during light sleep, particularly the N1 stage, to introduce specific themes or memories into dream narratives [6, 16, 17]. A related method, Targeted Memory Reactivation (TMR), applies previously primed sensory stimuli during sleep to trigger reactivation

Table 1: Summarization of Interactive Systems for Dream Engineering

Dream Engineering Technique	Description	Examples of Dream Engineering Systems
Targeted Dream Incubation (TDI)	A protocol designed to introduce or incorporate a specific theme, stimulus, or memory into dream content.	Involves serial auditory cues administered during light sleep (N1) using devices like Dormio[16, 18]
Targeted Memory Reactivation (TMR)	A related method where a sensory stimulus (like an odour or sound) associated with prior learning during wakefulness is re-presented during sleep to trigger the reactivation and strengthening of those specific memories.	Olfactory wearables like Essence or Ezzence can release scents during specific sleep stages (e.g., SWS) to enhance memory consolidation [2, 3]
Targeted Lucidity Reactivation (TLR)	A technique combining targeted cues with pre-sleep training to specifically induce lucid (the dreamer is aware they are dreaming) dreams.	Uses visual or auditory stimuli paired with lucid mind-state training to increase lucid dream occurrence in both laboratory [25] and home settings [27], like LuciEntry [48]
Dream Direction (DD)	Applying a sensory stimulus only during sleep to influence dreams, relying on existing implicit or direct associations of the stimuli rather than priming	Using pleasant scents to positively modify dream emotions, somatosensory stimulation to enhance dream movement sensations, or audiovisual stimuli to influence dream features, like DreamThrower [22] and DreamCeption [49]

of specific memory traces [1], for example, implementing olfactory cues during slow-wave sleep (e.g., [2, 3]). Another technique, Targeted Lucidity Reactivation (TLR), combines targeted cueing with pre-sleep metacognitive training to induce lucid dreams, which are states in which dreamers become aware they are dreaming and may exercise volitional control over dream content [27]. Dream Direction (DD) takes a more minimalist approach, bypassing pre-sleep association training and instead applying sensory stimulation directly during sleep to trigger related dream phenomenology, relying on inherent stimuli qualities [9]. Examples include using scents to modulate dream emotional valence and somatosensory stimulation to enhance sensations of movement [40].

2.3 Research Gap

While prior work has demonstrated the feasibility of modulating dream content through interactive systems, existing research faces two fundamental limitations.

First, a significant accessibility gap exists between consumer-grade and clinical-grade sleep sensing technologies. Laboratory-based PSG remains the gold standard for sleep staging, combining EEG, EOG, and EMG to reliably differentiate sleep stages through expert visual inspection of established neural and physiological markers. However, PSG requires clinical infrastructure, expert technicians, and costs that render it inaccessible for most users outside research contexts. Conversely, consumer-grade EEG devices (e.g., Muse [28], Dreem [4]) prioritize affordability and ease of use but sacrifice sleep-stage classification accuracy, particularly in the brief, transitional stages (N1, REM) critical to dream engineering interventions. This conflict between inaccessible clinical-grade systems and accessible but inadequate consumer devices represents a fundamental barrier to translating laboratory findings into effective real-world dream engineering applications.

Second, current approaches predominantly target singular sensory modalities: auditory cues delivered during hypnagogia [16], olfactory stimuli administered in slow-wave sleep [3], and somatosensory feedback during REM [12]. This single-modality approach does not reflect how natural dreams integrate multiple senses, restricting the potential richness of dream interventions.

2.4 Research Contribution

Dreamware addresses both limitations through an integrated system that combines laboratory-grade sleep staging with coordinated multimodal stimulation. We present two main contributions: First, we contribute a validated sleep staging system for real-world dream engineering. Dreamware employs a lightweight, hydrogel-based flexible EEG wearable with a deep learning algorithm that achieves 92.23% accuracy (Cohen's κ = 0.84) for REM sleep classification and 63.00% accuracy (Cohen's κ = 0.615) for N1 classification (substantially exceeding typical automated N1 classification rates of approximately 40% [13, 14, 30]. This capability bridges the accessibility gap between consumer-grade and clinical-grade sleep staging systems, enabling the translation of laboratory dream science into everyday contexts.

Second, we contribute an integrated system for multimodal dream stimulation. Prior work has demonstrated that isolated sensory channels can modulate dream content, yet naturalistic dreams seamlessly integrate visual, auditory, tactile, olfactory, and thermal sensations. Dreamware bridges this gap as the first out-of-the-lab system to deliver synchronized, closed-loop stimulation across all five modalities within a unified architecture, enabling interventions that more closely approximate the multimodal richness of natural dreaming and potentially yielding more immersive dream engineering experiences.

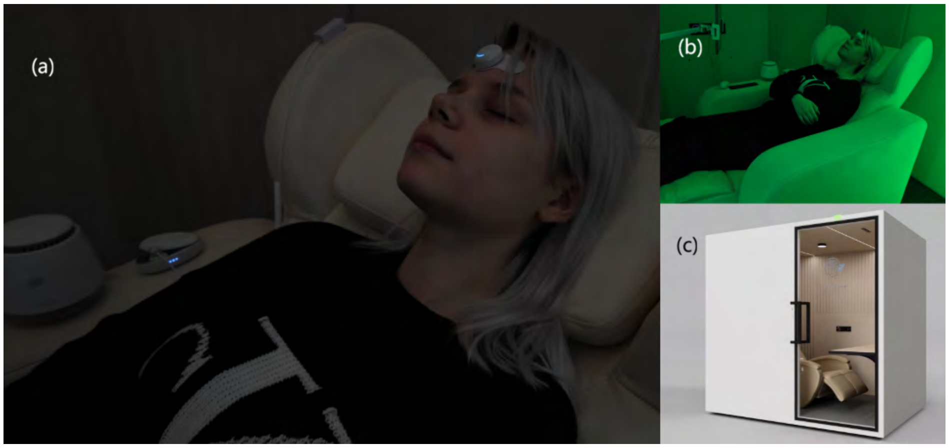

Figure 1: The Dreamware system. (a) A user using the Dreamware system. (b) Multi-sensory stimulation environment with green light stimuli. (c) Dreamware's design.

3 THE SYSTEM

The system architecture comprises both sensing and stimulation components: a patch-form hydrogel-based flexible wearable for sleep staging, a mobile application for data transmission and coordination, and five stimulus delivery channels targeting auditory, olfactory, visual, somatosensory, and thermoceptive modalities through a speaker, a scent diffuser, RGB LED lights, an instrumented sofa bed, and an air conditioner respectively (Figure 1. For details of system architecture, see Figure 2). The sensing component uses a single-channel wireless EEG wearable that we designed. The device samples at 250 Hz and captures frontal brain activity via the Fp1–Fp2 electrode differential, positioned according to the international 10-20 system [23].

Dreamware implements a closed-loop pipeline enabling real-time intervention. EEG signals captured by the wearable are transmitted to a mobile application via Bluetooth, which forwards the data to a cloud server over WiFi. Upon detecting a target sleep stage for dream engineering (N1 and REM sleep), the cloud server triggers programmed coordinated stimulus delivery across all connected devices: playing audio cues through the speaker, releasing scents via the diffuser, modulating ambient lighting, activating vibrations of the instrumented sofa bed, and regulating temperature to enable precisely timed multimodal interventions.

4 THE REM SLEEP DETECTION ALGORITHM

We developed an automated sleep staging algorithm using a lightweight CNN-LSTM architecture, where the CNN extracts salient features from raw EEG signals and the LSTM captures temporal dependencies across epochs. The model was trained on data from 44 participants (10 males and 34 females) who underwent two consecutive nights of sleep monitoring in a hospital. The study was approved by the Institutional Review Board at Hangzhou Seventh People's Hospital (The Affiliated Mental Health Center of Zhejiang University School of Medicine). Physiological signals were recorded simultaneously by both the PSG sleep stage [7, 8] and the Dreamware system during the study. Staging was performed in 30-second epochs, each subdivided into five 6-second sub-epochs. The algorithm achieved robust performance in REM sleep detection, with an overall accuracy of 92.23% and Cohen's κ of 0.84, indicating near-perfect agreement with expert-scored ground truth. For N1 detection, the algorithm achieved an accuracy rate of 63.00%, with Cohen's $\kappa = 0.615$ reflecting moderate agreement with expert-scored ground truth (the accuracy of automatic sleep staging systems for N1 remains low, often around 40% [13, 14, 30].

5 DREAM ENGINEERING PROTOCOL

The protocol targets both the hypnagogic state (N1) for high rates of direct incorporation and the REM state for complex narrative integration [9, 16, 17]. We present the protocol using the theme "forest" as an illustrative example (Table 2).

(1) Pre-sleep Priming: The participant undergoes a 15-minute intentional rehearsal phase, while multimodal stimulation is applied, building an association between the relevant stimuli and the theme [16].
(2) N1 Dream Incubation Loop: Upon detecting the N1 sleep stage, the system initiates the TDI loop. The system executes serial auditory prompts with the designed multimodal stimuli [16].
(3) REM Dream Engineering Loop: Upon detection of stable REM sleep, the system initiates TMR to foster complex theme-based narratives [1, 3].
(4) Closed-loop Adaptive Stimulation: Throughout the sleep session, the system continuously monitors EEG signals to detect transitions between sleep stages.

By combining these five modalities, the protocol attempts to create a "phenomenally-functionally embodied simulation [9, 50]" of a forest.

6 SAFETY AND ETHICAL CONSIDERATIONS

Multisensory stimulation during sleep necessitates careful attention to safety and ethics. Stimulus parameters must be calibrated to avoid sleep disruption, and the closed-loop architecture is designed to suspend stimulation upon detecting signs of arousal. We

Table 2: The details of the dream engineering protocol for the theme forest, based on the 5 modalities included in the Dreamware system [10, 38]

Modality	Stimulus Configuration	Rationale
Olfactory (Scent)	Release bursts of pine, eucalyptus, or tea tree essential oils via the scent diffuser	Olfactory cues bypass the thalamus with direct connections to the amygdala and hippocampus, modulating dream emotions without inducing arousal [40, 42]
Audio (Sound)	Serial auditory prompts (e.g., Remember to think of a forest); supplemented by ambient soundscapes (birds chirping, wind rustling)	Semantic cues guide dream content; ambient soundscapes enhance immersion and plot-following during REM sleep [15, 26]
Visual (Light)	Low-frequency green photic flicker delivered via room lighting	Light pulses during REM are often incorporated as flashing sunlight through leaves, lightning, or glowing forest elements [36]
Somatosensory (Vibration)	Mechanoreceptive stimulation via vibrating mattress with high-frequency vibrations and rhythmic pulses	Evokes sensations of bodily movement or rustling brush [32, 36]
Thermoceptive (Temperature)	Lower ambient temperature to 16–20°C (60–68°F) upon detection of REM sleep via connected air conditioner or thermal sheet	Cooler air could be incorporated as a refreshing forest breeze. [41, 52]

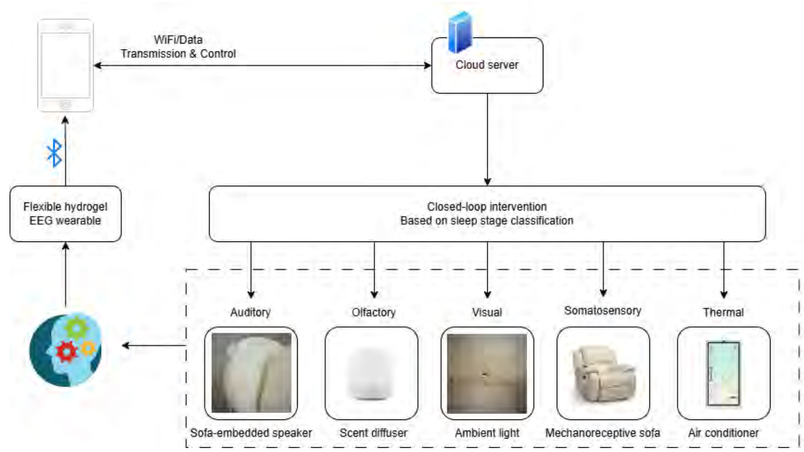

Figure 2: Dreamware's system architecture. The flexible hydrogel EEG wearable transmits real-time EEG signals via Bluetooth to a mobile device, which relays data to the cloud server for sleep stage classification. Upon detecting target sleep stages, the closed-loop intervention module coordinates multi-sensory stimulation across five modalities: auditory (sofa-embedded speaker), olfactory (scent diffuser), visual (ambient light), somatosensory (mechanoreceptive sofa), and thermal (air conditioner).

align our work with the emerging ethical principles of the dream engineering community [19]. In accordance with the principle that dream experiences belong to the individual, Dreamware is designed to enable rather than enforce dream modification. No intervention is delivered without explicit prior consent about the designed theme. To minimize the impact on natural sleep architecture, the closed-loop system suspends stimulation upon detecting signs of arousal or sleep stage transitions. Participants will be screened using validated sleep disorder questionnaires and excluded if clinically indicated, following established protocols in dream engineering research (e.g. [48]). To safeguard participant privacy, all collected EEG data and personal information are encrypted and stored securely, with third-party access permitted only upon the user's explicit informed consent.

7 THE NEXT STEP

Our research agenda will focus on empirical validation of Dreamware across therapeutic and cognitive enhancement applications. For therapeutic benefits, we will investigate whether multimodal affective dream modulation can be applied to nightmare disorders and emotional regulation. For cognitive enhancement, we will examine sleep-based learning paradigms that pair educational content with multimodal stimuli during waking, then redeliver these cues during dreaming to strengthen memory consolidation. We will also examine user experience factors, including wearable comfort, sleep quality impact, and subjective arousal disruption. Through these investigations, we aim to provide empirical evidence for coordinated multimodal dream engineering, establish design guidelines for interactive dream systems, and expand HCI's understanding of dreams as a design space.

8 CONCLUSION

This paper presented Dreamware, a brain-computer-interfaced multisensory capsule room contributing a PSG-validated sleep staging algorithm and the first integrated platform delivering synchronized, closed-loop stimulation across five sensory modalities: auditory, olfactory, visual, somatosensory, and thermoceptive. We hope this work inspires future research that designs dreams as a programmable design space, extending human–computer interaction beyond waking cognition and into the architecture of sleep itself.

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