Dozer: Towards understanding the design of closed-loop wearables for sleep

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Figure 1: Dozer being worn to bed.

ABSTRACT

Sleep plays a paramount role in maintaining healthy bodily functioning. Yet, poor sleep is an increasingly prevalent global health concern. Most current sleep technology tracks sleep, but how to design for promoting sleep is relatively underexplored. We highlight the potential of employing closed-loop systems for promoting sleep onset and explore this through the design and study of "Dozer", a closed-loop beanie that accelerates sleep onset through auditory and electrical brain stimulation after detecting drowsiness in EEG. In an in-the-wild study, participant interviews revealed three UX themes (closed-loop neurocentric agency, awareness of hardware, and awareness of feedback), which ultimately suggested that participants fell asleep in spite of Dozer, rather than through its assistance. We interpret these results and provide actionable design tactics to inform the design of closed-loop sleep systems moving forward. We hope this work gives rise to a deeper understanding of designing closed techno-physiological loops.

CCS CONCEPTS

• **Human-centered Computing**; • **Human-computer interaction (HCI)**; • **Interaction paradigms**;

KEYWORDS

brain-computer interface, closed-loop, EEG, tACS, sleep, neurostimulation, wearable

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1 INTRODUCTION

Sleep has been shown to have a definitive impact on cognitive functioning, mental health and physical health [24, 28, 41]. We need sleep to carry out our daily activities, maintain homeostasis and bodily functions, and ultimately, live. With this considered, maintaining healthy sleep habits is a vital aspect of life [48]. However, health concerns regarding poor sleep are becoming increasingly prevalent on a global scale [50, 53]. Contemporary technological solutions deployed to address the issue of poor sleep largely take the form of sleep tracking devices and applications [36], which are met with considerable user challenges. These include discontinuity in tracking as a result of the user falling asleep before providing input, intermittent use as a result of lifestyle factors, or users facing difficulties in interpreting how the data might inform them how to improve sleep [37]. Similarly, while there has been some progress in understanding the design of interactive technologies for sleep - for example using virtual reality to guide users to sleep or train sleep skills like lucid dreaming [32, 57] - such approaches also introduce their own disadvantages, including the potential for interrupting sleep onset to interact with the technology.

Meanwhile, recent neuroscientific works have explored neurostimulation paradigms to induce sleep conducive brain activity as a means of improving aspects of sleep health such as sleep quality and efficiency. For example, studies demonstrated the positive effects of transcranial electrical stimulation (tES) on sleep and the overall wellbeing of people [26, 66]. Zhou and colleagues focused on auditory stimulation, specifically pink noise, to modulate brain activity as a way to improve sleep stability [65]. Furthermore, studies applying neurostimulation to improve sleep have found that strategically timing stimulations with specific bodily rhythms, like certain stages in the sleep cycle, improve the efficacy of the stimulation [47]. These works involved controlled laboratory studies of specific stimulation paradigms and their consequential influence on neural dynamics, usually for clinical applications. The efficacy of these techniques in improving sleep health highlights a potential for their incorporation in interactive technology to improve general sleep well-being in non-clinical settings. With this considered, we see an opportunity to combine novel interaction paradigms, which are becoming increasingly prevalent in HCI, such as biosensing, with contemporary sleep neurostimulation techniques identified in neuroscience research. We aim to bring these developments together to explore closed-loop wearables (systems that can bidirectionally sense and actuate the wearer's physiology) [39] that can administer sleep-promoting stimulation outside the lab.

We investigate these ideas through the design and study of a novel system called "Dozer", a closed-loop wearable that accelerates sleep onset through auditory and electrical brain stimulation after detecting drowsiness in EEG. In this paper, we detail the design and evaluation of Dozer, which we evaluated through an in-the-wild study involving 11 participants who were instructed to use the prototype in their everyday life. Through thematic analysis of participant interviews, we uncovered three UX themes: closed-loop neurocentric agency, awareness of hardware and awareness of feedback, which ultimately suggested that while Dozer bestowed participants with a sense of agency over the system, they nonetheless fell asleep in spite of Dozer, rather than through its assistance. We interpret these results and provide actionable design tactics to inform the discussion and design of closed-loop sleep systems moving forward. We hope this work gives rise to a deeper understanding of designing closed techno-physiological loops.

2 RELATED WORK

Over recent years, HCI research has been increasingly interested in tracking, mediating and augmenting sleep using interactive technology [14, 27, 49, 57]. Our research builds on these advancements and our understanding of designing interactive systems for improving sleep onset. We will first discuss previous work related to sleep detection and then some of the ways researchers have tried to modulate and induce sleep.

2.1 Detecting sleep

We draw from previous work that establishes the benefit of tracking sleep, which has been found to be beneficial for improving cognition in ageing [26] as well as treating depression and insomnia [28].

There exist several ways to track sleep. Commercial technologies include easy-to-wear biosensing rings and wrist bands to monitor sleep patterns [25, 33], though these devices are usually restricted to sensing heart rate or movement and thus have limited accuracy. Comparatively, electro-encephalography offers an auspicious, relatively low-cost method of reliably detecting sleep stages [43, 61]. An electroencephalogram (EEG) tracks brain activity, including changes in the frequency and amplitude of this activity at various electrode sites over the scalp. Changes in the relative presence of activity within different frequency bands are indicative of sleep stage. Previous work has also established the presence of increased activity in lower bands (i.e., delta (1-4Hz), theta (4-8Hz) and alpha waves (8-12Hz)), relative to activity in higher frequency bands (i.e., beta (13-30Hz) and gamma (above 30Hz)) can indicate sleep onset [30, 31, 54].

Early EEG devices required laboratory setups with complex equipment, necessitating the presence of trained technicians, usually for the purpose of clinical research [7, 40, 59]. However, modern EEG headsets are available in a variety of forms, with varying electrode numbers, types, and costs, making them more portable, wearable and accessible. These developments allow for the study of sleep and the design of sleep-related technologies in newer and more varied contexts beyond clinical or classical research applications [12]. For instance, Koushik and colleagues designed a portable EEG device compatible with smartphones to track sleep [34]. Furthermore, there has recently been a renascence of consumer EEG devices currently available to the public. These systems enable laypeople to perform physiological monitoring on themselves approaching clinical quality. Such devices include the Dreem [6], and Muse-S [13] headbands, both offering automated sleep staging capabilities that allow users to receive detailed information about their sleep physiology.

However, while commercial EEG systems for automated sleep staging have been demonstrated to effectively track sleep, commercial devices are yet to directly improve sleep, instead relying on the user to interpret and act on the data they acquire through the device. While this is not necessarily a bad thing, as such practices can guide users toward healthier sleep habits, there also exist trade-offs with this approach, namely in that it has been documented that users find it difficult to act on the information provided [37]. Similarly, systems that track sleep and provide feedback are often trusted as an objective measure by the user, and if this contradicts the user's lived experiences, it can result in feelings of annoyance, stress and even anger [46].

We aim to improve upon devices that accurately track sleep, to develop technology also capable of modulating sleep onset, with guidance from the literature in the ensuing section.

2.2 Modulating sleep-related activity through contemporary technology

To improve sleep, researchers and clinicians recommend exercise, thermoregulation, nutrition, soothing music, and sleeping pills [1, 10, 15, 35, 64]. Still, these routes may not be effective or maintainable for some people. Also, though effective, sleeping pills can result in side effects, addiction, and the loss of control or autonomy [23, 62].

While medical research and its focus on pharmacological intervention has historically dominated the scientific discourse in sleep modification, recent work in HCI has begun to explore alternative technologically guided means to influence sleep physiology that are arguably less invasive. For example, "Inter-dream" [57], which promotes sleep onset, demonstrated how neurofeedback can push people toward a pre-sleep psycho-physiological state. The associated study involved users lying down on a bed and experiencing soothing music, while viewing imagery generated from their EEG projected onto the surrounding walls. While the system encourages subjects to a sleep state, it does not aim to maintain that state, especially considering wearing an HMD is not conducive to sustained sleep throughout the night. Furthermore, the system was not a wearable system accessible for home use, as it requires the presence of two artists to curate elements of the system's processes.

The "Lucid Loop" system also explored the use of EEG data from a wearable headband, as well as heart rate and breathing data from photoplethysmogram, gyroscope and accelerometer devices, to provide biofeedback for awareness of lucidity [32]. Changes in band power of different frequency bands from the EEG signal affected the clarity of audio and imagery of a virtual reality (VR) experience, using a head-mounted display. Through this feedback, users could try to change their brain activity to affect the VR experience. While the technology in this example does not directly influence sleep-related physiology, it trains skills that users can employ while dreaming in order to modulate their sleep physiology themselves. "NapWell" also explored VR, with the aim of decreasing sleep onset latency using imagery as a perceptual distraction [49]. Although these methods could promote better sleep outcomes with consumer-ready technologies, they require active engagement from the user, which could impede sleep onset. Taken together, these systems showcase contemporary technologies for supporting user-generated physiological regulation for sleep, highlighting opportunities for closed-loop systems to extend the mechanisms observed through using these systems by exploring system-generated physiological regulation.

Several neurostimulation techniques have been shown to affect sleep, and if exploited to their full potential, could pose as a panacea for addressing inadequate sleep and sleep inefficiency [26, 66]. Zhou and colleagues have shown a positive effect of electrical stimulation on sleep, using transcranial direct current stimulation (tDCS) to alleviate insomnia [66]. The authors demonstrated that stimulating the dorsolateral prefrontal cortex using tDCS was associated with increased sleep efficiency to alleviate insomnia, as well as treat depression.

Auditory stimulation has also been shown to promote sleep. Speech and other auditory cues have been shown to affect dream imagery [11]. In terms of affecting sleep quality, music researchers found that while music may not be effective in improving sleep [35], pink noise can. Pink noise refers to any signal that has a power spectral density that is inversely proportional to the frequency of the signal, which happens to be ubiquitous in biological systems including human speech, and may enhance sleep onset and quality due to its ability to entrain less complex, slow wave, neural activity [55, 65]. Researchers examined this phenomenon by varying volume levels of pink noise on healthy volunteers with normal hearing [65]. The authors concluded that pink noise exposure can be an effective and non-invasive way of improving sleep, bypassing the disadvantages of other methods discussed above including drugs and their side effects, sleep tracking devices limited to providing feedback, complex polysomnography units that are inaccessible to lay people, and devices that require active engagement by the user.

In summary, after reviewing prior work and relevant technologies, we have come to identify a research gap.

2.3 Research Gap

Prior works have demonstrated methods of detecting sleep, and how to positively impact sleep onset using a range of techniques. However, combining detection methods and stimulation to modulate sleep in a single closed-loop system has not yet been explored. Previous research in neuroprosthetics and human-computer integration has demonstrated that closed-loop design approaches to systems that interact with human physiology are associated with improved user experiences, improvements to intervention outcomes, and general benefits in overall well-being [8, 39, 63]. Therefore, the gap in knowledge is how to design a system that would utilise a combination of sensing and stimulation in a wearable factor, here, to support sleep onset. This leads us to begin answering the following research question:"*How should we design closed-loop technological experiences for sleep*?"

3 SYSTEM DESIGN

To begin answering the question above, we designed "Dozer". Dozer is a novel, wearable, non-invasive, closed-loop system to positively impact sleep onset, whose components are embedded in a beanie that users wear on their heads. Through the scalp, electrodes measure brain activity to produce the EEG, transcranial electrical stimulation (tES) electrodes stimulate the brain, and small embedded speakers play pink noise to further stimulate the brain towards sleep onset. Dozer is a non-invasive way of promoting sleep onset in an everyday environment. We aimed to design a versatile system that is able to be used during the day or at night when sleeping is

Figure 2: Dozer components. Left shows the front of Dozer with the outer layer removed, exposing the inner hardware. This includes the OpenBCI Cyton board for EEG data acquisition, a Cyton Bluetooth dongle to transmit EEG to the raspberry pi, a raspberry pi zero which is powered by a lipo battery, processes EEG data and initiates stimulation, a foc.us tES device that administers the tACS stimulation after receiving an initiation command from the raspberry pi, and a power port and switch to charge and power on/off the device. Right shows the back of Dozer with the outer layer removed, visible are the EEG electrode wires entering the beanie from the back, along with two headphones for administering pink noise stimulation after receiving an initialisation command from the raspberry pi, as well as ear clip electrodes that serve as ground and reference for the EEG. In both images, most of the hardware is tucked into the fold of the beanie.

desired. The following sections give an overview of the system's architecture and design.

3.1 System Architecture

Dozer consists of components encased within two layered beanies, to provide comfort and prevent parts being detached or taken apart, illustrated in Figures 2, 3 and 4.

Dozer includes 7 dry EEG comb electrodes placed at T7, T8, P7, P8, O1, Oz, O2 positions according to the International 10-20 system, and 2 ear clips for A1 and A2 signals. These project through the under-most beanie layer to contact the scalp directly, and connect to a Cyton Biosensing Board via Dupont wires. The beanie itself was of the "fishermans beanie" style, which was chosen due to its tight fit to encourage more stable electrode contact with the participant's scalp. We initially considered a headband, which was more aligned with what might be considered conventional sleepwear, however, we found we were unable to mount all of Dozer's hardware on such a small form factor. We then considered a sleeping cap for similar reasons but found that the materials and fabrics used in their design made them too pliable to ensure EEG electrodes maintained proper contact with the scalp. Only seven EEG electrodes were used in an effort to minimise bulkiness and support parsimony in the system. The positions (pictured in Figure 3) were chosen based on evidence that they outperform other positions in classifying drowsiness in various machine learning models [42].

The Cyton Board's associated dongle (RFD22301) is connected to a raspberry pi Zero 2 via a micro-USB adapter. The raspberry pi is also connected to an Adafruit I2S Audio Bonnet, which controls a pair of small speakers located on the sides of the head. A Foc.us V3 Multi-function Electrical Brain Stimulator, also connected to the raspberry pi, controls two tACS sponge electrodes placed at each temple and contacts the skin directly. Dozer is powered with a Polymer Lithium Ion Battery of 3.7 volts connected to the raspberry pi, which can be recharged via a small easily accessible charger port. Components are connected by appliance wiring material that can withstand up to 300 volts. The layered components are hidden from the user (Figure 4), except for a small switch at the front of the beanie to allow the user to turn the system on and off.

3.2 EEG Processing

EEG data processing was done using various packages in Python v3.7, including `BrainFlow`, `scipy`, `numpy`, and `pandas`. Data was sampled at 256Hz and sent from the Cyton Board to the Raspberry Pi to be analysed live. Data was analysed in 10 second epochs, which has been shown to be an appropriate length to fulfil assumptions about stationarity of the signal, necessary for epoch-based analyses [16, 17]. This provides the additional advantage of mitigating some of the negative impact signal noise generated artefacts, such as movement, might have on classification.

For each channel, a 10s epoch of raw EEG signal was z-score normalised, using the scipy `zscore` function. Data over 3 standard

Figure 3: Dozer complete. Left shows the front of Dozer with its outer layer on, which is how participants would have experienced the beanie. The right shows the inside of Dozer, which would be the part that makes contact with the participant's head. Note the EEG electrodes positioned along where the beanie would make contact with the back of the head, and the tACS sponge electrodes positioned at the user's temples.

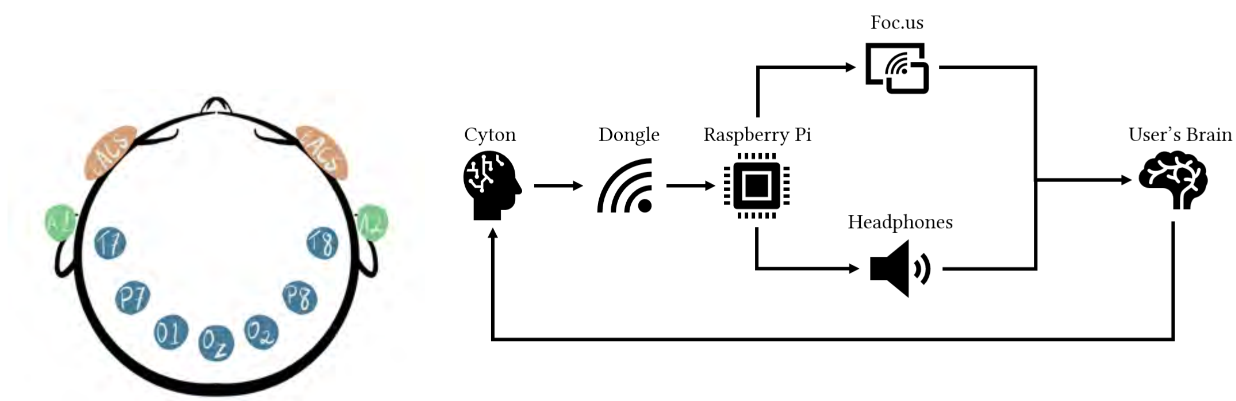

Figure 4: Schematic of Dozer electrode positioning (left) and a schematic of Dozer's closed-loop control circuit (right).

deviations from the mean was clipped at that value to reduce outliers likely to be artefact or noise. Power Spectral Density was obtained using the Welch method by constructing a BrainFlow `DataFilter` and calling the `get_psd_welch` method, specifying 256Hz as sample rate, fast fourier transform window size as the sample rate (which is already a power of 2), a windowing overlap of half the window size as is standard, and a Blackman-Harris window function. Alpha and theta band power were obtained using the `get_band_power` method of `DataFilter`, feeding in the power spectral density and limits of the frequency bands as 8-12Hz for alpha and 4-8Hz for theta. The relative ratio of these bands was then obtained by dividing theta power by alpha.

This ratio was used to indicate the onset of drowsiness, as suggested by previous research, where a higher theta-alpha ratio correlates with ratings of drowsiness [52]. The average theta-alpha ratio over all 7 channels was then computed. Three epochs in a row in which this value exceeded a threshold were required to trigger the stimulation, described in the next section.

The theta-alpha threshold was obtained by prior analysis using EEG data recorded using the Dozer headset. We wanted to use a threshold appropriate for the particular array of electrodes and hardware, since power has been found to vary according to different electrodes and references [60]. Therefore, using Dozer, we recorded 5 minutes of eyes-closed, and 5 minutes of eyes-open, resting but wakeful activity from the authors of the study. From this data, we constructed a distribution of theta-alpha ratio values using a bootstrapping method. Specifically, we randomly sampled 10s epochs from the recordings, calculated the theta-alpha ratio values using the same steps described above, and added them to a distribution 10,000 times for the 'eyes-open' and 'eyes-closed' condition separately (Figure 5 below). The 95th percentile of these distributions were 1.31 and 1.32 respectively. We therefore decided on the threshold value of 1.3, with the understanding that we expect values to exceed this ratio 5 percent of the time, and argue that requiring three epochs in a row may be sufficient to indicate drowsiness, which occurred less than 0.07 percent of the time using the above bootstrapping sampling method.

3.3 Electrical Stimulation

In the literature, transcranial electrical stimulation (tES) techniques have been described as a successful way to stimulate the brain and promote sleep onset [26, 66]. Transcranial electrical stimulation is a classification of neuromodulation that releases weak electrical currents through electrodes connected to the head. This stimulation technique is broken down into 3 types of stimulation: Transcranial direct current stimulation (tDCS), transcranial random noise stimulation (tRNS) and transcranial alternating current stimulation (tACS). We opted to employ a tACS stimulation protocol, as it uniquely affords the ability to entrain specific neural oscillations in the brain, such as oscillations associated with sleep, which has demonstrated efficacy in previous literature [22].

Once stimulation has been triggered to begin after the stages described in the previous section 3.2, the raspberry pi initiates the Foc.us V3 brain stimulator, which lasts a total of 10 minutes after which it will be switched off, and a cooldown of 8 hours prevents re-initiation of stimulation. The device was set to provide a bipolar alternating current stimulation of 0.65mA at a frequency of 5HZ, as suggested by previous lab studies [22].

3.4 Auditory Stimulation

The auditory stimulation was inspired by Zhou and colleagues (2012) who recruited 40 participants and exposed them to pink noise and observed its effectiveness [65]. The authors used pink noise that ranged from 20dB to 40dB. The result was a significant decrease in brain wave complexity leading to an improvement in sleep stability. With the evidence that sounds delivered through bone conduction can enhance slow neural oscillations associated with sleep, Grimaldi and colleagues (2020) showed that pink noise is an effective technique for sleep enhancement [26]. Limitations of acoustic stimulation include the lack of clarity on the quantitative delivery of sequential tones to achieve an optimum enhancement of sleep onset and how long the stimulation should last.

The Dozer system is equipped with a pair of speakers sewn into the beanie to output the pink noise. The speakers are connected to the Adafruit I2S Audio Bonnet using the audio port which is in turn connected to the raspberry pi that does the necessary processing to yield the sound for 8 hours. This is the generally understood appropriate sleep duration on average for adults [29].

3.5 System Breakdown

Figure 6 shows how the system functions as a whole once switched on by the user. EEG data detects increased relative band power of theta to alpha waves to indicate drowsiness. Once the system induces that the user is beginning sleep onset as noted by an increase in measures of drowsiness, the raspberry pi – which is connected to the speakers and Foc.us brain stimulator – will start the auditory pink noise and electrical tES stimulations, which will last for 10 minutes. During stimulation, EEG recording is stopped to avoid contaminating the EEG signal with tACS activity. On initiating stimulation, an eight-hour cooldown is initiated to prevent re-initiation of stimulation while the user is sleeping, preventing a situation where re-initiation of auditory stimulation might wake the user. The system can be switched off at any time if needed.

4 METHODOLOGY

The following section discusses the methods employed to carry out our in-the-wild study and evaluate our system, Dozer.

4.1 Participants

11 participants were recruited through advertisements through our lab's mailing list, social media posts, and word of mouth. They include 6 males, 4 females, and 1 non-binary or self-described with ages varying from 22 to 34 years (*M*=27.27, *SD*=4.58). Previous literature has suggested a number of populations may be prone to adverse as a result of tES [5], and as such, we employed exclusion criteria preventing said populations from participating. This included: a history of brain surgery, head trauma, and/or cognitive deficit, history of tumor, stroke, seizures, epilepsy or other intracranial diseases, implantation of intracranial metal, pregnancy, and repetitive migraine.

4.2 Procedure

The study's procedures were approved by the ethics board of our institution. After informed consent was obtained, participants were given the system and instructed on how to use it, including how to power and charge it, how to operate it and how to correctly place the electrodes at the back of their heads.

The in-the-wild study aimed to understand the user experience afforded by the system. Participants used the system at home for 24 hours. There were no given or prescribed tasks that the participants had to complete, as we were interested in understanding how participants chose to use Dozer. Participants were instructed to use Dozer whenever they found it convenient – during night-time or during the day for a quick nap – and to take note of the system's ease of use and effectiveness. After turning Dozer on, the system acted as described in the System Design section, to analyse brain waves and initiate electrical and auditory stimulation if adequate drowsiness was detected.

Afterward, participants took part in an online interview to answer a series of semi-structured interview questions lasting for approximately 30 minutes. Participants were recorded during the interviews and their answers were later transposed into text.

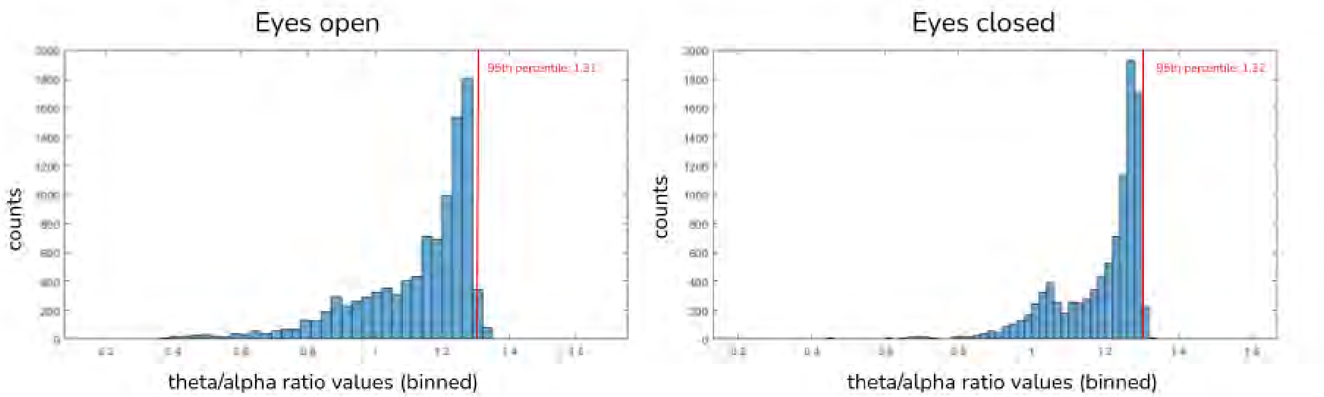

Figure 5: Distributions of theta/alpha ratios from bootstrapped 'eyes-open' and 'eyes-closed' data.

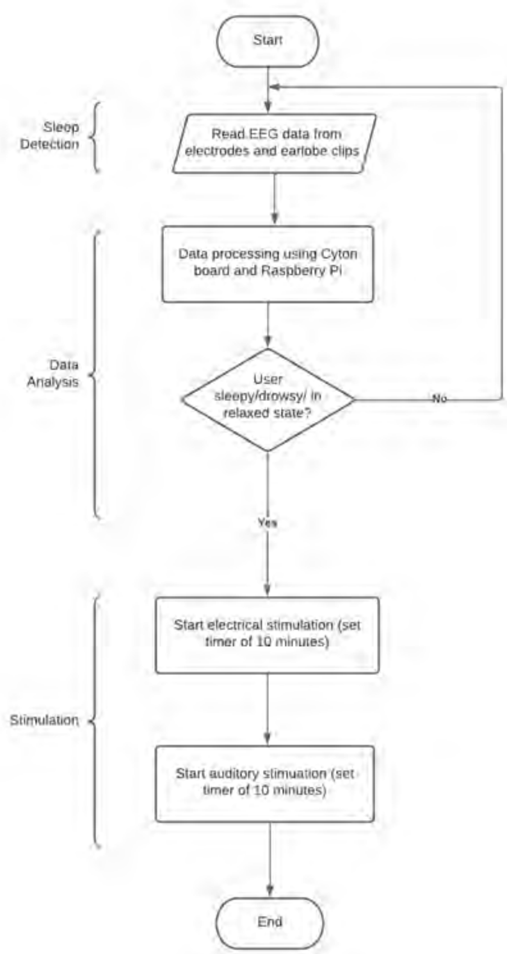

Figure 6: Flowchart of system logic.

5 RESULTS

To understand the user experience of closed-loop wearables for sleep as probed through the prototype, thematic analysis [9] was conducted on transcripted interviews regarding participant experiences. Through our analysis, three overarching themes were revealed that together described the user experience of closed-loop wearables for sleep as experienced through Dozer. Thematic analysis of the collected data was performed inductively, where three researchers independently reviewed transcripts and participant diaries and coded the data. Each "unit" of data is a single coded quote, a practice we borrow from others [3] that benefits the reader by providing a means of gauging the frequency and thereby prevalence of codes relating to the given theme occurring throughout interviews. Codes were iteratively clustered into high-level groupings agreed upon between researchers until they were consolidated into two final themes emerging from the data. The following sections investigate these results further by articulating the themes: closed-loop neurocentric agency, awareness of hardware, and awareness of feedback.

5.1 Closed-loop neurocentric agency

The theme "closed-loop neurocentric agency" is composed of 66 units of data and describes participant experiences relating to being in a closed-loop, with the system both sensing and stimulating them.

To begin, when prompted to explain the system as they understand it, participants had consistently conceptualised it as closed-loop, with statements such as "*I say it would be trying to detect if you are sleepy and then if you are, it would try to make you more sleepy or make you fall asleep quicker*" (P1), and "*It reads your brain activity and depending on certain wave patterns, it will determine when to start functioning and once it starts, it will reinforce what's already happening. And that thing that's happening is basically you being sleepy*" (P6). Participants also compared it to other closed-loop technologies, stating "*It's kind of like wearing a heart monitor that knows when you are breathing hard and your heart rate goes up and it does something.*" (P2). However, there were some instances in which the closed-loop nature of the system was not entirely clear, with one participant stating "*So basically I would just say that when you go asleep, just put it on and then just do nothing more than just sleep. You hear some kind of noise*" (P8), suggesting that they assumed the stimulation was scripted to activate regardless of the brain activity. The emphasis of stimulation over sensing was further echoed by participants who did communicate an understanding of the system's closed-loop properties, recounting that they often forgot about the "sensing" half of the system, which in their mind was overshadowed by the "stimulating" half, with P7 stating "*I was more focused on the fact that there was gonna be feedback, I forgot about the fact that it was also reading*". This may be a result of the system's lack of feedback regarding its inner functioning, and participant experiences of apprehension or expectancy toward an approaching stimulation, which will be further discussed in section 5.2.

When the system did eventually detect sleepiness and administer stimulation, participants were again reminded of the fact that the system was sensing them. This was primarily noted in that retrospectively participants believed the stimulation was administered at an appropriate time based on how they were feeling when it was initiated, with statements such as "*it was at the point in which your thoughts become kind of dream, like your mind just starts generating its own content and that's like when it activated*" (P1), "*my mind had quietened a bit, like I wasn't, as consciously thinking about certain things and having an internal discussion with myself about then I was more just like laying there, I think by the time that first vibration happened*" (P5), and "*timing of it did make sense because I'd stopped moving around and was definitely like feeling more sleepy*" (P7). We note, however, that in some instances this was not always the case, with some participants believing "*it was random*" (P3), and some participants not noticing any stimulation taking place at all (P9 and P10). Similarly, P2 recounted that they had fallen asleep before the stimulation started, and only found out they had been stimulated after their partner told them they heard the pink noise playing from their beanie. However, P2 retrospectively still believed the timing of the stimulation made sense, stating "*I was obviously sleepy when it started*" (P2).

Nonetheless, participants that did perceive their stimulation often recounted a sense of feeling that they caused it to happen. P2 stated "*it felt like it was coming for me, even though I didn't do it consciously, I felt like my brain flicked the switch that activated it*". Similarly, P6 described "*I wouldn't say anything remarkably unique happened wearing the beanie through the course of the night. It just felt like I was going to sleep as usual wearing a beanie. So if I got tired, I feel like [the activation] would've just been my own brain*", suggesting that a stillness in activity would lead to a brain state change regardless. P3 also described that "*it felt like I did something and it started [...] I was thinking, did I do something with my brain? [...] I was the trigger for it somehow, even though I don't know what I did*". When questioning P3 further about whether the system could be designed differently so they would not feel they initiated the stimulation, they stated "*it should probably be like no instructions [...] and then it would feel like the machine is in control*". This suggests knowledge about what the system is doing is important to feeling a sense of agency, a notion which will be further discussed in 5.2. P5 similarly stated that "*my brain activity triggered the beanie, producing noise*", and then likened it to how people listen to noise to help them sleep, saying it's "*something similar to that, but just being triggered by your brain waves instead of being triggered by you rather than asking Alexa, or just playing it off Spotify to put you into sleep, so it's an automated solution with brain-computer interface*". When further prompted as to whether they thought it being activated from the brain made a difference, they replied stating "*from what I can see there is a fundamental difference since I'm not doing it consciously. My body is telling the interface when to do it. And if in the other option I do it consciously, I'm putting myself in that phase. But in the experience with the beanie, it's not something born out of choice, but it is something born out of the condition that my body is in or my mind is in. I have tried playing white noise multiple times, and mostly on the days where I have to fall asleep, but most of the time I end up not falling asleep because I'm just trying too hard to do it. So that's the difference between this experience and that one. This is not something that you are forcing yourself through, it's just helping you get to that state*". Here, we can see that through developing a sense of bodily agency through anticipating the system's functioning as an extension of their bodily processes, participants can nurture a sense of trust toward the system and its stimulation, perceiving it as something that knows when to initiate an attempt to sleep rather than their own executive decision making. This notion of trust is echoed by other participants, especially when likening it to medication, with P6 stating "*if you were to take medication before going to sleep, it felt like I was taking those similar sort of steps. I was using some kind of technology that I kind of just gotta place my trust in. I was just like, yes, this is how I'm gonna go to sleep, and thinking of it as a kind of medicine made me feel cared for in a way*".

5.2 Awareness of Feedback

The theme Awareness of feedback is composed of 42 units of data and describes how feedback regarding what the system and their brain were doing, or lack thereof, influenced participants' experience.

To begin, participants reported experiences of uncertainty, anticipation, mysteriousness, and confusion which also impacted their ability to fall asleep, which was attributed largely to the black-box-like design of the system that gave little feedback regarding its functioning and operation. Concerns about whether the system was working properly were common, with statements such as "*I guess I just never knew if I had it in the right position or anything*" (P6), "*Besides turning on the system, I am not quite sure what else I did with it, so I would describe it as mysterious*" (P3), and "*I guess personally I wasn't aware of how it was programmed to do what it did and I guess I just kind of presumed that it was more on some kind of timer or maybe that it would just trigger if something happened that was always going to happen*" (P7). Participants also described a feeling of anticipation or apprehension wondering whether and when the stimulation would come, with P1 describing "*I was actually thinking about [the stimulation] a lot before it happened like, when's it gonna happen? When's it gonna happen?*" and P2 saying "*I was waiting for it, I wasn't sure if something was gonna happen*". Participants were worried that their metacognitive thinking of the stimulation might interfere with the system's processes, with P8 stating "*I think I was overthinking it. And so potentially that maybe messed up the stimulation or I was just so distracted and missed the stimulation entirely*", and "*it made me overthink if it was gonna work*

[...] it's really hard if you're an anxious sleeper because you overthink it too much and it just really confounds whatever effect [the system] is supposed to have" (P2). This often resulted in introspective feedback loops that made participants feel more mentally active "*I was probably more self-aware I suppose, I was trying to be aware of what was going on in my head to see if there were differences*" (P7), and "*I was definitely bit curious and I was also wondering how long it will last, but I was also wondering whether the sensations I was feeling would intensify at some point. And maybe me thinking about it, would make it intensify*" (P8), and "*maybe because I was so aware, it just thought I was, my brain was being productive and it wasn't picking up on me actually in a really tired state. So it never applied the effect. So maybe I just passed out cause I was exhausted*" (P9).

Considering this, many participants explained how they felt they would like more feedback, with P5 stating "*there was nothing to give me feedback if the position for the electrodes were correct, so maybe a calibration phase might help*", and P8 similarly explaining "*maybe I'd prefer some kind of feedback, I don't know if it would maybe defeat the purpose, but maybe implementing some feature [to] the device so that when you put it on your head you can actually see the person's brain activity in some way*". P5 explained how they believed that informational and reference content would be a sufficient form of feedback, stating they would have preferred "*a photo of how it looks like to be properly wearing it, with the beanie being a bit translucent in the image so that the wearer can see where the actual position it's supposed to be*" and also stated they would appreciate an "*indicator for the user to know that the device, worked when they felt asleep*". P3 further explained that they believed that having the user know what the system was doing was important for them to have a sense of agency over it, and further imagined this could be achieved through a narrative-based voice-guided experience, stating: "*I don't think a visual interface is required because, I would have appreciated even just basic voice instructions using the speaker that was embedded into the headset, not interrupting the flow of the experience, but rather just being very subtle*". They likened this to guided meditation sessions, and explained that "*it can even be like a bedtime story or designed to be a bedtime story before the actual experience starts off*". Taken together, it appears this theme suggests that the lack of feedback regarding how or if the system was functioning influenced participants' ability to sleep by drawing their attention to the system in anticipation, and that some form of feedback that users can optionally access may alleviate this tendency.

5.3 Awareness of Hardware

The theme "Awareness of Hardware" is composed of 46 units of data, and describes how participant experiences were heavily shaped by the physical design of the system and how they perceived it in relation to their body.

The theme awareness of hardware first becomes evident through the comments made by participants describing the wearability of the system. Specifically, many participants found Dozer to be an uncomfortable experience that impacted their ability to sleep. P6 stated "*I think there are electrodes in the back, spikey dudes, and that made it difficult to sleep in my favourite position, which is on my back, so I had to sleep on my side, which is something I don't like doing. I had a really troublesome sleep, it was like one of those fever dreams*". Here we can see the user being made aware of the system's presence through discomfort, manipulating the sleeping behaviour of the participant, thereby having a negative impact on their sleep quality. This was not only a product of the dry electrodes, which participants often described as "*spiky*" (P1, P2, P6), making it "*hard to find a nice position*" (P2), but also due to the presence of the many electronic components that were necessary in giving the system closed-loop capabilities. Participants stated "*I guess being aware of all the circuitry you've got up there made me really careful with my head movements, I was worried I was gonna unplug something accidentally*" (P6), "*I was trying to be really delicate with it*" (P7). Furthermore, participants also described how they were prepared to give up comfort, mobility, and even subject themselves to pain in order to facilitate the operation of the system, with comments such as "*I just tried to sit on my back because I thought I'll lie on my back because even though it was painful, it would probably, make the best contact between my head and the electrodes and make the system work better*" (P1), and participants described how they avoided moving, even though this created discomfort, because "*I was worried that if I moved my head around a lot, maybe I would mess up the readings a bit*" (P6). Overall, these accounts suggest that there was a tradeoff between wearability and data quality, with participants demonstrating some degree of willingness to sacrifice wearability in service of the system.

In addition to the physicality of the system, participants also explained how making the stimulations themselves less noticeable would improve the experience by drawing less attention to the beanie's presence. Specifically, minimising the attention drawn to the beanie and making the stimulations less perceptible would allow Dozer to be experienced as an extension of themselves rather than an external device. P1 stated "*If, one, you couldn't feel the immense physicality of it and two, you didn't really notice the stimulation and it just felt like you were going to bed, I think that would feel like it would be completely synergizing with your body or it be a part of your brain*" and said that "*a slow ramp up would make it less noticeable*". P2 explained that "*the fact that it was really uncomfortable makes it hard to feel like it's physically a part of you*" and P10 similarly stated that "*it didn't seem natural for me. I think I was pretty aware that it was from the headset, I didn't think that it was coming from me, from my body or from my brain*". Participants highlighted that the dichotomy between the headset and their body interrupted sleep, with P6 saying "*if I'm certain the technology is working, putting aside the question as to maybe it didn't turn on or something I'd probably rather not feel any feedback*", further stating "*I don't want it to interfere with me falling asleep, but also, I feel like it would just feel more natural. You'd feel less like you are wearing a beanie, that's supposed to put you to sleep. I feel like it would help you not obsess about it too much*". This suggests that beyond improving the wearability, knowledge regarding how the system works, rather than direct feedback being provided by the system during its use, may be more congruent with the aim of designing closed-loop systems for sleep promotion. Participants suggested time and experience with the system may be a good source of this "feedbackless feedback", stating they would feel "*more integrated*" with the system if it was "*something that I was using a lot*" (P7). Similarly, P5 explained "*if maybe I would have it for, let's say the whole duration of my day, and then gone to* *sleep wearing it, then maybe it would've been a bit different, but just wearing it [...] and then going to sleep, it did feel like another wearable that I'm trying to achieve a functionality with*". P1 also stated that "*I can imagine if I used it a hundred times, maybe it would feel like, oh, this thing's reliably knowing when I'm sleepy*" and P2 explained that "*I just wish that we could have used it for longer probably because I think that would've really allowed the identification of patterns better, or to get a better feel for the system too, because it's just really hard to know from one night, to develop a relationship with it, I guess, which is sort of what you do with stuff like this*". Taken together, this suggests that a combination of familiarity, knowledge and understanding, and wearability, can allow wearers to experience closed-loop sleep technologies as transparent, integrated interfaces.

6 DISCUSSION

In contrast with our aim of designing a closed-loop system to support sleep onset, our results indicate participants fell asleep in spite of the system rather than through it, with Dozer apparently disrupting sleep onset. Specifically, participants appeared to demonstrate a high sense of agency over the system's functioning, yet felt disconnected to the system due to lack of feedback, lack of understanding of the system's hidden processes and lack of familiarity with the system, coupled with a constant reminder of the beanie's presence due to some challenges with its wearability. Nonetheless, despite failing to reach our desired user experience, the results presented above provide valuable insights in furthering our understanding of designing closed-loop systems for sleep.

First, we notice that our three themes, closed-loop neurocentric agency, awareness of feedback, and awareness of hardware, correspond strongly to the "bodily integration" design space, as defined by Mueller and colleagues [38, 45]: "sense of bodily agency" and "sense of bodily ownership", which many others have used previously to describe similarly closed-loop systems [2, 4, 18–20, 38, 56, 58]. This connection was not preemptively sought after, but rather became evident following the analysis of Dozer's user experience. The bodily integration design space is a design space that describes the design and associated user experience of "bodily integrated" systems, systems that couple human biology and computational machinery to allow for bidirectional actuation and ultimately, integration between form and function of humans and computers. With this considered, it makes sense that the user experience of Dozer maps well to this design space, as Dozer bidirectionally links the human and computer through both sensing and stimulating the brain, thus serving to validate the bodily integration design space, while also indicating that Dozer can be considered a "bodily integration system". The dimension of "sense of bodily agency" describes to what extent the user experiences they have causal influence over the system. Systems with a high sense of bodily agency promote experiences in which the user feels "I did that" when perceiving system output. Inversely, low bodily agency systems promote experiences in which the user does not experience the functioning of the system as something they initiated. The sense of bodily agency dimension corresponds strongly with our theme of closed-loop neurocentric agency, as seen by quotes such as "*it felt like it was coming for me, even though I didn't do it consciously, I felt like my brain flicked the switch that activated it*" (P2). This demonstrates that Dozer could be considered to have a high sense of bodily agency, while also suggesting that systems with a high sense of bodily agency need not have explicit inputs, but rather can also be implicit (meaning that the user is not required to consciously initiate causal influence over the system in order to feel in control), extending existing knowledge regarding the design of bodily integrated systems. In regard to the bodily integration design space dimension of "bodily ownership", systems that are experienced as extensions of the user's body can be said to have high bodily ownership, while systems experienced as another body or an external device possess a low sense of bodily ownership. This corresponds strongly with our themes of awareness of feedback and awareness of hardware, as demonstrated by participants describing the system, stating "*it didn't seem natural for me. I think I was pretty aware that it was from the headset, I didn't think that it was coming from me, from my body or from my brain*" (P10). This indicates that Dozer facilitates a low sense of bodily ownership.

Using the bodily integration design space to further unpack the experience of Dozer, it could be said that the system facilitated a high sense of bodily agency, and a low sense of bodily ownership, leading to a user experience Mueller et al. would name "tele-body" [38], suggesting a disjointed and distanced experience between the user and the system. This comes as a slight surprise, considering Mueller et al. use drones and tele-presence robots to exemplify tele-body systems [38], however, our findings may suggest physical distance may not be an important factor in differentiating tele-bodies from "superbodies" (systems which posses both a high sense of bodily agency and bodily ownership). Furthermore, our results suggest that as the awareness of the hardware or "low sense of bodily ownership" undermined the system's ability to promote sleep onset, future systems should instead aim to facilitate a high sense of bodily ownership and thus aim toward a "superbody" user experience, which Mueller et al. describe as systems that elevate the user's bodily abilities and facilitate superhuman-like experiences (superhuman sleep onset in this instance) [38].

6.1 Design Tactics

Considering the interpretation of our results, alongside its relation to previous literature, and our own craft knowledge gained through the design and deployment of Dozer, we now articulate a set of design tactics to help designers of closed-loop systems for sleep learn from the shortcomings of Dozer to ultimately facilitate their desired user experience and promote sleep. It can be said that these tactics are mainly aimed toward increasing sense of bodily ownership to allow systems like Dozer to facilitate "superbody" type experiences.

Consider personalisable feedback. One strategy Mueller et al. provide for supporting bodily ownership is to consider offering the opportunity for personalisation in the design of the system [38]. Immediately obvious avenues for facilitating personalisation in future iterations of Dozer-like system would be to offer adjustable beanie sizing as well as swappable EEG electrodes for different head sizes and hair types. However, referring to our results, it also becomes evident that personalisable feedback may be greatly beneficial to increasing a sense of bodily ownership. While participant opinions regarding feedback was varied, it was consistent that they mainly wanted feedback to learn and understand the system to build a relationship of competency and trust with it, but would rather have little to no feedback during sleep onset so as to not disrupt the process of falling asleep. With that considered, we suggest including some form of feedback that users can refer to in order to confirm that the system is functioning, while also providing information such as their concurrent brain state, or wheather they were stimulated the night before. The amount of feedback should be customisable such that users can choose to turn it down or discard it outright as they grow more comfortable and develop a stronger relationship with the device. Furthermore, Mueller et. al suggest feedback modalities such as engaging localized sensations including those felt mainly through touch, pain, proprioception, kinesthesia and temperature as good candidates for promoting high bodily ownership [38]. However, we also caution designers to keep feedback minimal so as to not disrupt sleep onset.

Consider ramping stimulations for lower perceptability. Our results indicated that participants found the sudden stopping and starting of both the auditory and electrical stimulation jarring, with participants sometimes being drawn out of sleep as a result. With this considered, we recommend tapering the sound level of the auditory stimulation over many minutes in order to reduce this effect. Tapering stimulation onset may also help deal with discomfort caused by electrical stimulation, as studied indicate slowly ramped voltage can lessen sensations such as tingling, burning and phosphenes [51]. Also, the system had a set of predefined settings for the level of electrical stimulation and pink noise emitted. While this makes Dozer an automatic sleep monitoring and staging system, having the possibility to adjust the settings to some extent could increase the experience of comfort and agency in the user. These adjustments could be done by linking the system with an electronic device that would allow users to control the settings and adjust them according to their personal preferences.

Consider balancing wearability to lower physical awareness of hardware. Closed-loop systems can be difficult to contain in a wearable form factor due to the necessity for the system to house both sensing and actuating capabilities. As such, the designer may often have to prioritize between data quality and user comfort. For example, wet cold cup electrodes would have provided us with better data and more accurate readings, but they would also necessitate that users coat the electrodes with gel or paste, making for a very messy sleep, thus leading us to adopt dry comb electrodes. However, participants still suffered discomfort due to the stiffness of the dry comb electrodes, which tended to dig at the back of their head. The placement of electrodes at the back of the head was another wearablity versus data quality trade-off, in which we opted for back-of-the-head placement due to the area's involvement with sleep-related electrophysiology and performance in other systems [42], However, this made it more difficult for participants to sleep on their backs as this caused the electrodes to dig deeper into their scalp. Alternatively we could have opted to place flat dry contact electrodes across the forehead, which should still be able to adequately detect changes in the theta-alpha ratio, and improve wearability, thereby making the sleeping experience much more positive for the participant. Such positions should still adequately measure changes in the theta-alpha ratio. With this considered, we suggest designing for wearability over data quality in sensitive contexts such as sleep, as lack of comfort may have a greater effect on data collection than instrument quality.

6.2 Limitations and Future work

A limitation of this study was the short length. Participants noted that their experience of the system may have been different if they had the opportunity to become more familiar with Dozer and how it functions. Considering this, we suggest future in-the-wild studies can use our design as a starting point for a longer deployment to help understand the complex temporal interactions afforded by closed-loop wearable sleep systems.

We believe that our study could be supplemented with controlled lab studies to allow for a better evaluation of the efficacy of Dozer-like systems. While user accounts suggest that Dozer did not improve sleep onset, quantitative confirmation of this observation would assist in informing future iterations of Dozer-like systems.

We considered assessing efficacy to be beyond the scope of our present work, with previous work already demonstrating the efficacy of neurostimulation [22]. Rather, in exploring the phenomenological experience afforded by Dozer, and discussing these experiences within the framework of human-computer integration [44, 45], we were able to craft a grounded articulation of design strategies from a user experience perspective. With the present study being exploratory in nature, the research aimed to uncover experiential factors in closed-loop sleep systems, such that future work may then operationalise and assess these factors to determine efficacy and other objective measures. Furthermore, by opting for an in-the-wild study, we were able to procure rich naturalistic data providing a clearer understanding of how such technologies may be used and experienced in a real-world setting. With this considered, we now suggest how our preliminary results may be used to guide future quantitative research and assessment of efficacy below.

Further study of future iterations of Dozer-like systems could involve a lab-controlled study aimed at testing hypotheses centred on design and user experience factors, manipulating them to determine the nature of their relationships. For example, future studies could assess the relationships between closed-loop feedback, wearability, sense of bodily ownership, and sense of agency. These relationships could be investigated by testing hypotheses such as "decreased awareness of the system is associated with a significant increase in sense of bodily ownership", and "there is a significant relationship between awareness of system feedback and sense of agency". Such a study could also group participants by feedback modality (auditory, tACS, both) to assess its influence on efficacy, and group participants by electrode positioning to assess the trade-off between wearability and signal quality, as suggested by our last design tactic. These analyses could also be supplemented by analysis of other quantitative data, such as taskload, accuracy, sleep quality, and electrophysiological response. The results of such studies could inform the design of the next generation of Dozer-like systems that would be more performant in terms of efficacy and experiential integration with the user's body, which could again be assessed in in-the-wild studies to determine how these changes have altered the user experience from a phenomenological perspective.

In the case of a future in-the-wild study, further improvements to the system can be made for improving its capacity to collect quantitative data in the field. Specifically, we recommend that the system has impedance sensing capabilities to detect if electrodes have correct contact with the user's scalp. This information could be fed back to the user through a companion app, providing participants with a feedback channel that they can refer to if in doubt that the system is functioning correctly, which would also fulfil our design tactic"*Consider personalisable feedback*". Furthermore, while we selected electrode positions for detecting drowsiness at the back of the head based on recommendations from previous literature, this decision may have inadvertently introduced the potential for disrupting the signal during sleep-related behaviour, namely in that participants could not sleep on their backs without placing pressure on the electrodes. With this in mind, we again recommend future studies consider our tactic "Consider balancing wearability to lower physical awareness of hardware" and place electrodes in positions such as the forehead, which do not interfere with sleep-related behaviour, as most people do not sleep with their forehead contacting the pillow. Furthermore, the use of the forehead area would negate the need for the BCI to employ spiked or combed dry electrodes due to the absence of hair at the recording sight, and flat dry electrodes, thus improving the system's comfortableness. Furthermore, future studies could also strive to reduce the form factor to a headband as opposed to a beanie, as we originally intended. To do this we suggest employing fewer electrodes (specifically at (forehead locations such as Fz, F1, F2, F3, F4), using a phone instead of an onboard raspberry pi for data processing and classification, and choosing between employing auditory or tDCS stimulation rather than both.

We also did not investigate different permutations of the different stimulations - whether auditory may be more effective if used alone, or visa versa. Another limitation is the scope of the present study in that we only explored one kind of "closed-loop". Specifically, our system was designed to amplify user state, by detecting sleepiness and aiming to increase it. However, we could also investigate a negative feedback loop, for example regulating sleep by detecting stress or other qualities that negatively impact sleep, and aiming to combat those.

Furthermore, looking at recent research on interaction design for head-based wearables could also further guide future work towards new iterations of Dozer systems. Specifically, Dierk et al.[21] suggest that the designer consider the physical form of the hardware, and how personal and public information could be communicated, paying attention to tangible landmarks. For future iterations of Dozer-like systems, this could mean taking advantage of features already present on the sleep headwear the system is being integrated into to communicate to the user feedback that might help them make sense of if the system is working and what it is doing. For example, a system integrated into a traditional sleeping cap with a pompom at the top could have embedded LEDs that change colour depending on signal factors such as signal quality. Furthermore, we suggest considering the headwear's inherent function, noting that the technology should not conflict with what the garment was originally intended to do. For Dozer-like systems, this could mean avoiding the incorporation of feedback modalities that the user must attenuate to, such as a display. Finally, we suggest considering the context of use, and the opportunities for unique interactions these contexts offer. For Dozer-like systems, the context of use is obvious (sleep), and one example of making use of this context would be to embed wireless charging capabilities into the user's pillow, allowing the user to charge the device while sleeping.

7 CONCLUSION

In this paper, we argued that recent discoveries in neuroscience paired with a closed-loop bidirectional design paradigm present an opportunity to explore a new class of interfaces that may improve sleep onset outside of the lab. We explored this opportunity through the design and study of a novel system we have developed called "Dozer", a closed-loop sleep wearable that accelerates sleep onset through auditory and electrical brain stimulation after detecting drowsiness in EEG. To understand the associated user experience afforded by the system, we deployed the system in an in-the-wild study where 11 participants engaged in open-ended unrestricted use of the system over 24 hours, from which we found through participant interviews the prevalence of three themes: closed-loop neurocentric agency, awareness of hardware, and awareness of feedback. These themes suggested that while the closed-loop nature of the design allowed partcipants to experience the system with a high sense of bodily agency, the awareness of the system's hardware that was brought on by features detracted from any efficacy it might have had in promoting sleep onset. Considering these results together, we produced a discussion of insights learnt about the user experience and design space of closed-loop systems for sleep, providing a theoretical starting point for HCI researchers to begin discussing such systems. Furthermore, we extrapolate a set of design tactics from these insights as well as our craft knowledge in building the system to guide engineers and designers in developing closed-loop systems for sleep. It is our hope that this work inspires the emergence of a line of research exploring the boundary between sleep and technology.

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