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Contactless Stimulation for Sleep Enhancement via Mid-Air Ultrasound

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概要: Sleep involves active sensory processing, with tactile input playing a key modulatory role. This study used a contactless Airborne Ultrasonic Tactile Display (AUTD) system to investigate the effects of rhythmic tactile stimulation on nap quality. Results showed that participants achieved rapid sleep onset, accompanied by enhanced parasympathetic activity. These findings highlight the efficacy of ultrasonic tactile stimulation in promoting high-quality restorative naps and suggest new avenues for sleep modulation using non-contact sensory interfaces.

キーワード： Mid-Air Ultrasound, Sleep Modulation, Haptics

1. Introduction

In recent years, virtual reality (VR) applications have evolved from primarily focusing on immersive simulations and entertainment to encompassing relaxation experiences. As VR technologies increasingly strive to create calming, multisensory environments, a logical progression of this trend is the utilization of VR settings to aid in the initiation of sleep. Consequently, scenarios in which users either fall asleep or awaken within VR environments are becoming increasingly plausible. However, in efforts to relax and fall asleep, users typically close their eyes, rendering visual elements of VR unusable. In these instances of closed-eye usage, tactile stimulation emerges as a particularly significant sensory modality. This study investigates a novel application of mid-air tactile feedback within the context of sleep, with the objective of quantitatively assessing its efficacy in promoting sleep onset and enhancing sleep quality.

The tactile system, responsible for perceiving mechanical stimuli through the skin, is a crucial but often overlooked modulator of sleep quality and brain function. Despite the overall reduction in external sensory input during sleep, tactile stimuli continue to be processed, particularly during the stages of deep sleep.

Tactile input has been shown to modulate heart rate variability, sleep-stage stability, and latency of sleep onset, with individual differences in sensory gating influencing susceptibility to sleep initiation , [1]. Stimuli can also enhance slow oscillations and spindles, suggesting potential applications in sleep modulation.

In this study, we employed the Airborne Ultrasonic Tactile Display (AUTD) system to deliver consistent and contactless tactile stimulation. AUTD operates by focusing ultrasound waves via a phased array, generating localized radiation pressure in mid-air to stimulate the skin surface without any physical contact. This method offers significant advantages over traditional tactile stimulation devices. First, it eliminates mechanical contact, thereby avoiding issues such as skin adaptation, friction, or discomfort, which can affect the consistency of long-term stimulation [2]. Second, the stimulus parameters—including frequency, amplitude, and modulation patterns—can be precisely programmed, allowing for continuous and rhythmic tactile feedback suitable for sleep-related experiments [3].

The study shows that participants achieved rapid and high-quality sleep with AUTD stimulation, displaying a complete sleep cycle and positive autonomic states. This experimental setup has a notable capacity to induce superior restorative naps, exceeding results from typical nap studies.

2. Methods

Tsumoto et al. [4] developed a technique to generate pleasant stimulation using airborne ultrasound. Additionally, Loken et al [5]. reported that a stroking speed of approximately 10 cm/s is perceived as comfortable. Based on this finding, our study aims to induce sleep by applying pleasant stimulation to the forearm of relaxed subjects. Our experimental setup consists of eight ultra-

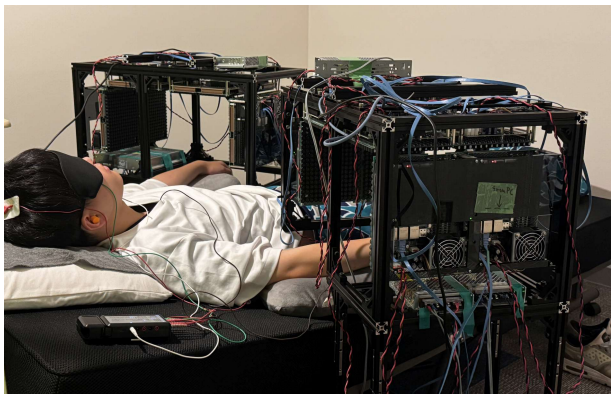

図 1: Photograph of the experiment in progress.

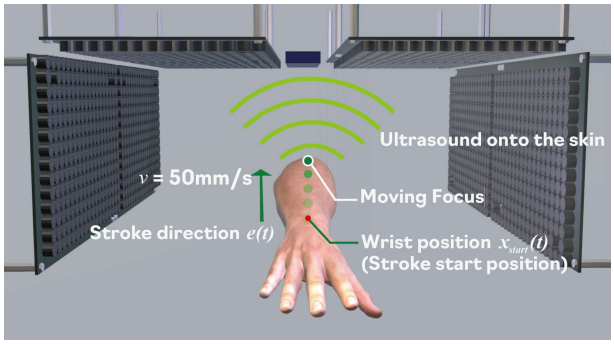

図 2: A schematic diagram of the tactile stimulus.

sound phased array devices placed on the upper part of each forearm (Fig. 1).

As illustrated in Fig.2, moving focus was applied along a linear trajectory extending 100 mm from the starting point $\mathbf{x}_{\text{start}}$ in the direction of the unit vector $\mathbf{e}(t)$. The STM frequency f_{STM} was set to 0.5 Hz, resulting in a stroking velocity of 50 mm/s. To prevent an increase in skin temperature due to prolonged phased-array irradiation, the focal point was positioned 5 mm above the skin surface to apply acoustic streaming [6].

3. Experiments

3.1 Measurement of Biosignals

In this study, multiple physiological signals are measured to assess the subjective sleep state of the participants. The recorded signals include, EEG and ECG.

3.1.1 EEG

Sleep is a dynamic process involving complex brain–body interactions and is typically divided into non-rapid eye movement (NREM) and rapid eye movement (REM) stages. NREM progresses from light (N1) to deep sleep (N3), while REM is marked by vivid dreaming and brain activity. Deeper stages like N3 and REM are essential for physical recovery, memory consolidation, and subjective sleep quality.

To monitor neural activity during the sleep experiment, we recorded electroencephalography (EEG) using the BioRadio wireless biopotential acquisition system (Great Lakes NeuroTechnologies, USA). EEG signals were sampled at 1000 Hz using a single bipolar channel (C4–O1),the placement of electrodes according to the international 10–20 system [7]. The reference electrodes were placed on the left earlobe, respectively.

For analysis, we adopted U-Sleep sleep analysis toolkit [8]. U-Sleep—a deep learning-based classifier—was used to validate sleep stage predictions with a data-driven approach, providing robust temporal resolution across multiple sleep cycles.

3.1.2 ECG

The sleep state analysis process based on heart rate variability (HRV) primarily relies on detecting R-waves in electrocardiogram (ECG) signals. By calculating the time intervals between adjacent R-waves (RR intervals), HRV metrics can be derived.

In this approach, the potential difference between the RA (right clavicle) and LL (left abdomen) electrodes is used as the primary lead (similar to the traditional Einthoven lead II). This configuration effectively captures R-wave peaks, provides stable signal amplitude, and offers a high signal-to-noise ratio, making it suitable for long-term recording and HRV analysis [9]. Once the ECG signal is constructed, bandpass filtering is applied to remove noise, R-wave positions are extracted, and continuous RR intervals are calculated.

The ECG data are then segmented into fixed time windows (5 minutes), and for each segment, the standard deviation of RR intervals (SDNN) and the root mean square of successive differences (RMSSD) are computed. These two metrics reflect overall heart rate variability and parasympathetic nervous system activity, respectively [10].

By observing the temporal trends of SDNN and RMSSD, one can infer the individual's sleep state during different periods [11].

3.2 Subjective assessment criteria

In this nap experiment, three questionnaires were introduced to comprehensively assess participants' subjective sleep states: the Pittsburgh Sleep Quality Index (PSQI), the Nap Habits and Background Questionnaire (NHQ), and the Nap Sleep Questionnaire (NSQ). Both the PSQI and NHQ were completed prior to the experiment.

3.3 Experimental Procedure

Before the experiment begins, to ensure that participants have a solid sleep foundation, researchers first ask them to complete the PSQI and NHQ.

During the preparation phase, operators follow stan-

dard procedures to attach electrodes required for EEG and ECG monitoring. Participants are then equipped with earplugs and an eye mask to block external disturbances. Once the participant has adjusted to a comfortable sleeping posture, the researchers proceed to orient and calibrate the AUTD device accordingly.

After confirming that all sensor signals are being stably and accurately recorded, the experiment officially begins. The AUTD device is activated, and the main lighting in the lab is turned off to create a sleep-conducive environment. The sleep induction phase lasts approximately one hour, during which EEG and ECG are continuously recorded.

At the end of the experiment, all physiological signal recordings are terminated and saved first. Then, gently awaken the participant, and the NSQ is completed within three minutes after awakening.

4. Results

All participants completed subjective questionnaires. Three reported normal sleep habits, while two showed signs of disturbance (PSQI scores 7 and 9). All subjects lacked habitual daytime napping. Overall, it is shown that no major discrepancies between perceived and measured sleep quality.

As shown in Figure 3, Figure 4, and Table 1, all five participants exhibited distinct sleep architectures during the nap session. Several subjects entered deeper sleep stages such as N3 and REM within a limited timeframe. Correspondingly, elevated RMSSD and SDNN values were observed, indicating increased parasympathetic activity and a shift toward restorative physiological states.

Notably, EEG-based sleep latency was shorter than self-reported estimates, likely due to altered time perception during sleep onset and the exclusion of initial wake periods in the final-hour EEG recordings. Among the participants, S2 and S5 showed the fastest transitions into N2 or REM sleep—consistent with their low PSQI and NHQ scores, reflecting better baseline sleep health.

While some discrepancies were present in perceived sleep latency, subjective and objective assessments of sleep quality showed strong alignment. The proportion of time spent in the sleep stages generally matched the depth and satisfaction of the participants' self-reported sleep, except for S4, whose elevated PSQI score suggested possible sleep disturbances.

表 1: Subject HRV Normalized Index (RMSSD and SDNN) .

Subject	RMSSD [-]	SDNN [-]
S1	0.438	0.497
S2	0.410	0.455
S3	0.509	0.651
S4	0.305	0.455
S5	0.566	0.549

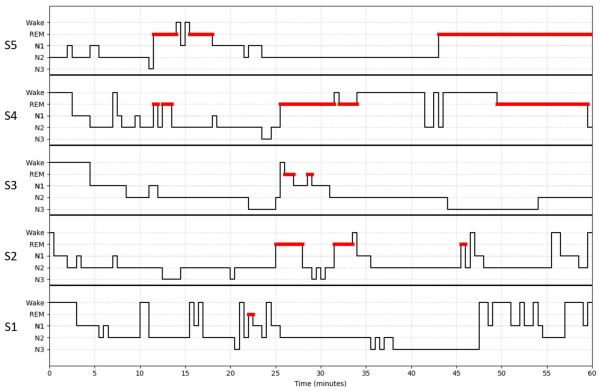

図 3: Hypnograms of all five participants during the nap session, showing temporal transitions across Wake, N1, N2, N3, and REM stages.

5. Disscussion

Compared to the existing literature, participants in this experiment demonstrated a significantly improved sleep quality during the nap period, as indicated by both sleep onset and sleep architecture metrics.

EEG analysis showed that all participants had a sleep latency under 10 minutes, notably shorter than the typical 10–20 minutes for healthy adults [12], suggesting

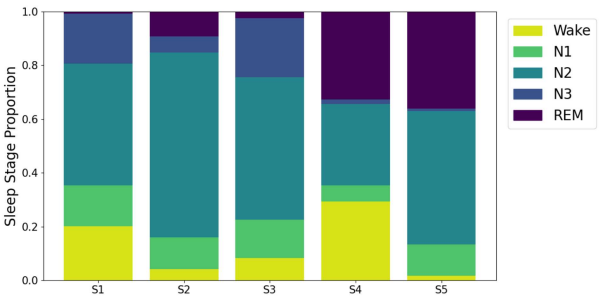

図 4: Integrated visualization of sleep architecture and HRV during daytime naps. Most subjects reached N3 or REM sleep within a relatively short duration, indicating that the experimental environment effectively facilitated high-quality, restorative sleep.

rapid transition into a relaxed, sleep-initiating state under experimental conditions.

Although previous studies report that N3 and REM sleep are uncommon during short naps under 30 minutes [13] , our experiment showed that four out of five participants entered REM sleep within this timeframe. Notably, S4 and S5 spent over 30 percent of their nap duration in REM, indicating that the experimental setup effectively promoted deep and restorative sleep.

HRV indices, particularly RMSSD and SDNN, reflected enhanced parasympathetic activity consistent with deep sleep. Participants S3 and S5 showed notably high RMSSD values (0.509 and 0.566), comparable to levels seen in nocturnal N3 sleep [14]. Their elevated HRV and extended N3/REM durations suggest a strong alignment between sleep architecture and autonomic regulation, characteristic of restorative naps.

However, it is essential to acknowledge that the current study did not incorporate a control condition devoid of AUTD stimulation. Consequently, the extent to which the noted enhancements in sleep quality can be directly linked to the tactile stimulation remains ambiguous. Future research employing randomized controlled designs is necessary to elucidate the specific role of AUTD in the modulation of sleep.

6. Conclusion

Taken together, the findings indicate that under the experimental conditions involving AUTD stimulation, participants were not only able to fall asleep quickly but also to achieve high-quality sleep in a brief period. The presence of a complete N1–N3–REM sleep structure, along with favorable autonomic states, is relatively uncommon in short nap studies, underscoring the significant potential of this experimental setting to induce high-quality restorative naps. These results surpass the typical nap architecture reported in most existing studies.

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参考文献

[1] Sofia Isabel Ribeiro Pereira, Felipe Beijamini, Frederik D. Weber, Roberta Almeida Vincenzi, Felipe Augusto Cini da Silva, and Fernando Mazzilli Louzada. Tactile stimulation during sleep alters slow oscillation and spindle densities but not motor skill. *Physiology Behavior*, Vol. 169, pp. 59–68, 2017.

[2] Takayuki Hoshi, Masafumi Takahashi, Takayuki Iwamoto, and Hiroyuki Shinoda. Noncontact tactile display based on radiation pressure of airborne ultrasound. *IEEE Transactions on Haptics*, Vol. 3, No. 3, pp. 155–165, 2010.

[3] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, pp. 505–514, 2013.

[4] Kai Tsumoto, Tao Morisaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Presentation of tactile pleasantness using airborne ultrasound. In *2021 IEEE World Haptics Conference (WHC)*, pp. 602–606, 2021.

[5] Line S Löken, Johan Wessberg, India Morrison, Francis McGlone, and Håkan Olausson. Coding of pleasant touch by unmyelinated afferents in humans. *Nature neuroscience*, Vol. 12, No. 5, pp. 547–548, 2009.

[6] Dario Pittera, Orestis Georgiou, Abdenaceur Abdouni, and William Frier. ï can feel it coming in the hairs tonight¨: Characterising mid-air haptics on the hairy parts of the skin. *IEEE Transactions on Haptics*, Vol. 15, No. 1, pp. 188–199, 2022.

[7] Report of the committee on methods of clinical examination in electroencephalography. *Electroencephalography and Clinical Neurophysiology*, Vol. 10, No. 2, pp. 370–375, 5 1958.

[8] Mathias Perslev, Sune Darkner, Lykke Kempfner, Miki Nikolic, Poul Jørgen Jennum, and Christian Igel. U-Sleep: resilient high-frequency sleep staging. *npj Digital Medicine*, Vol. 4, No. 1, 4 2021.

[9] Effect of different ECG leads on estimated R–R intervals and heart rate variability parameters, 7 2019.

[10] Fred Shaffer and J. P. Ginsberg. An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, Vol. 5, , 9 2017.

[11] David Herzig, Prisca Eser, Ximena Omlin, Robert Riener, Matthias Wilhelm, and Peter Achermann. Reproducibility of heart rate variability is parameter and sleep stage dependent. *Frontiers in Physiology*, Vol. 8, , 1 2018.

[12] Danielle Pacheco and Danielle Pacheco. Sleep latency, 7 2025.

[13] Janna Mantua and Rebecca M.C. Spencer. Exploring the nap paradox: are mid-day sleep bouts a friend or foe? *Sleep Medicine*, Vol. 37, pp. 88–97, 3 2017.

[14] Fred Shaffer and J. P. Ginsberg. An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, Vol. 5, , 9 2017.