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Cardiac and Sleep-Stage Responses to Rhythmic Auditory and Amplitude-Modulated Vibrotactile Pillow Stimulation During Daytime Naps

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ABSTRACT

Rhythmic pillow stimulation combining mechanical vibration and sound may influence cardiac activity and sleep progression. We compared Control, heartbeat-like Tapping with sound and vibration at 45 beats per minute, and Vibrotactile stimulation produced by amplitude-modulating a 50-Hz pillow vibration at 0.25 Hz in a within-subject daytime-nap experiment. Twenty-three participants completed all conditions. Electrocardiography and polysomnography were analyzed over the first 55 min without sleep-duration exclusions. Mean heart rate was evaluated by one-way repeated-measures ANOVA and Holm-adjusted paired comparisons; sleep-stage proportions and latencies by Friedman tests. Mean heart rate was 60.69 bpm in Control, 59.94 bpm during Tapping, and 58.01 bpm during Vibrotactile stimulation. The condition effect was nonsignificant ($F(2,44) = 2.08$, $p = 0.138$). Vibrotactile stimulation was 2.69 bpm lower than Control in the unadjusted paired comparison (95% CI –5.36 to –0.01, $p = 0.049$, Cohen's $dz = –0.43$), but not after Holm correction ($p = 0.147$). Sleep-onset latency was 7.57, 8.54, and 6.61 min, and N3 proportion was 18.62%, 15.10%, and 21.15%, respectively. N2 was reached by 22, 20, and 23 participants and N3 by 18, 15, and 18. Among participants reaching each stage in all three conditions, N2 latency was 13.68, 12.76, and 12.61 min ($n = 19$), and N3 latency was 20.96, 20.17, and 18.04 min ($n = 12$); neither condition test was significant. Vibrotactile stimulation showed a descriptive pattern of lower heart rate, more N3 sleep, and earlier N3 occurrence, whereas Tapping did not shorten sleep onset. Exploratory findings require confirmation in prespecified, adequately powered studies.

Keywords: Daytime nap, Heartbeat-like tapping, Vibrotactile stimulation, Amplitude modulation, Heart rate, NREM sleep

INTRODUCTION

Sleep-onset latency is an important indicator of sleep quality (Ohayon et al., 2017). Large-scale population research in Europe and North America has documented difficulty initiating sleep as a common complaint among adults, with prevalence varying by age, sex and country (Kocevska et al., 2021).

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These complaints motivate the development of nonpharmacological sleep-support technologies for everyday environments. Simplicity and unobtrusiveness are important user requirements for such technologies (Choe et al., 2011). We therefore focused on a pillow interface that presents sensory stimulation while the user rests without requiring a body-worn device, and examined two rhythmic patterns with distinct design rationales.

The first pattern was heartbeat-like Tapping, presented through sound and vibration. Acoustic-tempo experiments have shown that cardiac responses depend on the relationship between stimulus tempo and basal heart rate (HR) under paced breathing (Watanabe et al., 2017). Slow heartbeat-like wrist vibration has also reduced skin-conductance and subjective anxiety responses during an awake stress task (Azevedo et al., 2017). These findings informed the design of a slow external rhythm at 45 beats per minute (bpm), drawing on cardiac entrainment as a design concept. We used heartbeat-like sound and vibration with the aim of encouraging lower HR during sleep initiation, and examined cardiac activity and sleep initiation.

The second pattern, termed Vibrotactile, was inspired by whole-body rocking research. Bed rocking at 0.25 Hz shortened the transition to N2 during naps (Bayer et al., 2011), while whole-night rocking shortened N2 latency, increased N3 sleep and reduced NREM arousal density (Perrault et al., 2019). We used a 50-Hz carrier vibration amplitude-modulated by a 0.25-Hz envelope, delivered locally through the pillow, to examine progression toward deeper NREM sleep. The 0.25-Hz component describes the amplitude envelope, not an actual rocking movement of the sleeper.

Responses to rhythmic mechanical stimulation vary with stimulus mechanics and delivery method. Rocking studies report protocol-dependent changes in sleep architecture and EEG activity (Subramaniam et al., 2023; van Sluijs et al., 2020), and mouse experiments identify a role for otolithic function and acceleration (Kompotis et al., 2019). Whole-bed beat-frequency vibration and closed-loop mattress vibration studies further illustrate differences in stimulus delivery and sleep responses (Himes et al., 2021; Kwon et al., 2024). These differences motivate direct evaluation of cardiac and sleep-stage responses to localized pillow stimulation.

Sleep onset is a gradual transition in which electroencephalographic, behavioral and autonomic boundaries do not necessarily coincide (Biabani et al., 2023). Cardiac regulation also changes across wakefulness, NREM and REM sleep (Fink et al., 2018). Together, HR and sleep-stage measures provide complementary characterization of cardiac responses, sleep initiation and progression toward deeper NREM sleep.

This exploratory study compared Control, Tapping and Vibrotactile conditions in a within-subject daytime-nap experiment. We analyzed the first 55 min of each session, evaluating mean HR, sleep-stage proportions, stage attainment, sleep-onset latency, sustained-sleep latency, N2 latency and N3 latency. Guided by the stimulus design rationales, we examined whether Tapping was associated with lower HR and earlier sleep initiation, and whether Vibrotactile stimulation altered progression toward deeper NREM sleep.

The aim was to determine whether these two forms of rhythmic pillow stimulation elicited distinct physiological response profiles during sleep initiation.

METHODS

Participants and Study Design

This paper included 23 participants with electrocardiographic and sleep-stage recordings for all three conditions (20 men and 3 women; age 22.57 ± 1.56 years, mean ± SD; range 18–25 years). Each participant completed Control, Tapping and Vibrotactile conditions in a within-subject crossover design in randomized order. All 23 participants were included in the primary analysis, contributing 69 nap sessions. No exclusion was based on sleep duration.

Outcomes were 55-min mean HR, sleep-stage proportions, total sleep time, stage attainment, sleep-onset latency, sustained-sleep latency, N2 latency and N3 latency. Secondary outcomes were sleep-only mean HR and the change in mean HR from the first to the final 10 min (final minus first). Each outcome comparison used participants with values available in all three conditions.

Experiments were conducted in a sleep laboratory at Ritsumeikan University during daytime nap opportunities, approximately between 11:30 and 16:00. Each session allowed approximately 60 min for sleep. Participants were instructed to avoid caffeine, alcohol, smoking, and deliberate sleep restriction before each session. The institutional ethics committee approved the study (BKC-LSMH-2025-113), and written informed consent was obtained before data collection.

Stimulation Conditions

A pillow-type device with embedded speakers was used to present stimulation to the head (Figure 1). The speakers were positioned beneath the head so that their mechanical vibration was transmitted directly to the head through the pillow. Speaker operation also produced sound. Tapping presented a heartbeat-like rhythm at 45 bpm through sound and vibration. Vibrotactile stimulation consisted of a 50-Hz carrier vibration sinusoidally amplitude-modulated at 0.25 Hz. The 0.25-Hz component describes the amplitude envelope, not a rocking movement of the body. In Control, the same pillow was used without stimulus presentation. Figure 2 shows the temporal patterns of both stimuli.

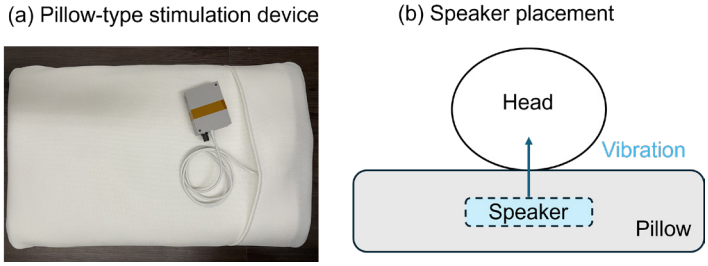


Figure 1: (a, left) Pillow-type stimulation device. (b, right) Schematic of the embedded speaker region beneath the head.

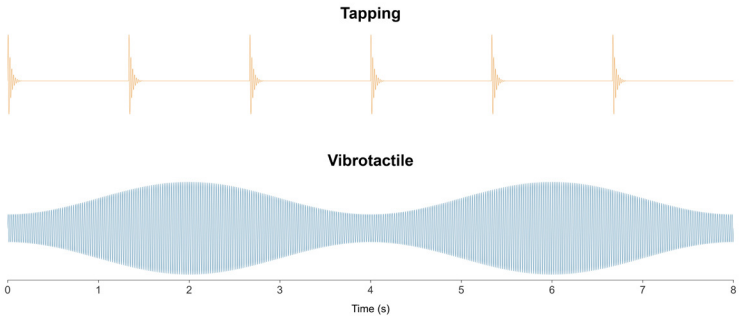


Figure 2: Waveforms of the Tapping (45 bpm) and Vibrotactile (50-Hz carrier with a 0.25-Hz amplitude envelope) stimuli used in this study.

Physiological Recording

Physiological signals were recorded with a Polymate V system (Miyuki Giken, Japan). Polysomnography included electroencephalography, electrooculography, submental electromyography, and electrocardiography. EEG was recorded from C3 and C4 (central) and O1 and O2 (occipital) according to the international 10-20 system. A1 and A2 were placed on the left and right earlobes and used as contralateral references, yielding C3–A2, C4–A1, O1–A2 and O2–A1 derivations. Frontal and parietal EEG was not recorded. Electrooculographic electrodes were placed near the outer canthi. Electrocardiographic electrodes were placed below the left clavicle and near the lower rib margin. Sleep stages were scored from these recordings according to AASM sleep-staging criteria. The present paper reports HR and the scored sleep-stage sequence.

Heart Rate Processing

R peaks were automatically detected from the electrocardiogram, and the detections were visually inspected against the ECG waveform. False detections and missed peaks were corrected with reference to the waveform. Intervals in which R peaks could not be reliably identified because of movement, poor electrode contact or similar artifacts were excluded. The resulting R–R intervals were summarized in consecutive 30-s epochs, with epoch HR calculated as 60 divided by the mean R–R interval in seconds.

The 55-min mean HR was the mean of valid epoch HR values from 0 to 55 min. Secondary outcomes were mean HR during epochs scored as sleep and the change in mean HR from the first to the final 10 min (final minus first). Each repeated-measures analysis included only participants with the outcome available in all three conditions.

Sleep Stage Processing

Sleep stages were classified in 30-s epochs using NightAwl (Norpro, Japan) as wakefulness, REM, N1, N2, and N3. Stage proportions were calculated over the available scored epochs within the 0-55-min window. Total sleep

time was calculated by summing the durations of 30-s epochs scored as sleep and converting the total to minutes.

Sleep-onset latency was the time from the beginning of the analysis window to the first non-wake epoch. Sustained-sleep latency required three consecutive non-wake epochs. N2 and N3 latencies were the times to the first occurrence of the respective stage. A stage that did not occur was treated as not attained rather than assigned an observed latency of 55 min. Stage-attainment counts were reported for the full 23-participant cohort, whereas latency comparisons used only participants who reached the target stage in all three conditions.

Statistical Analysis

HR outcomes across the three experimental conditions were evaluated using one-way repeated-measures ANOVA, followed by paired post hoc comparisons with Holm adjustment for multiple comparisons. Participant ID was the repeated-measures unit. Mauchly's test was used to assess sphericity, and Greenhouse-Geisser correction was planned when sphericity was violated. The ANOVA effect size was partial eta squared. Post hoc results included the paired mean difference, an unadjusted two-sided 95% confidence interval, raw and Holm-adjusted p values, and Cohen's dz.

Sleep-stage proportions, total sleep time, and latency outcomes were evaluated with Friedman tests because these measures included bounded proportions or skewed distributions. Pairwise comparisons used paired Wilcoxon signed-rank tests with Holm adjustment within each set of three condition comparisons for a given outcome. Descriptive statistics are reported as means and standard deviations, whereas nonparametric methods were used for inferential comparisons based on the distributional characteristics of these outcomes. Paired individual data plots were used for visualization. All tests were two-sided and $p < 0.05$ was treated as statistically significant. No multiplicity adjustment was applied across distinct outcome families because the analyses were exploratory. No sleep-duration exclusion was applied to the primary 23-participant sample.

RESULTS

Heart Rate

Mean HR during the first 55 min was 60.69 bpm in Control, 59.94 bpm during Tapping, and 58.01 bpm during Vibrotactile stimulation (Figure 3). Mauchly's test did not indicate a sphericity violation ($W = 0.965$, $p = 0.691$). The overall condition effect was not statistically significant, $F(2, 44) = 2.08$, $p = 0.138$, partial eta squared = 0.086.

In paired post hoc comparisons, Tapping HR was 0.76 bpm lower than Control HR (95% CI –3.83 to 2.31, raw $p = 0.613$, Holm-adjusted $p = 0.613$, $dz = –0.11$). Mean HR during Vibrotactile stimulation was 2.69 bpm lower than in Control (95% CI –5.36 to –0.01, raw $p = 0.049$, $dz = –0.43$); this difference was not significant after Holm adjustment ($p = 0.147$). Vibrotactile stimulation HR was 1.93 bpm lower than Tapping

HR (95% CI –4.62 to 0.77, raw p = 0.152, Holm-adjusted p = 0.305, dz = –0.31). Secondary analyses gave a sleep-only mean HR of 59.26, 57.60, and 56.59 bpm in Control, Tapping, and Vibrotactile conditions, respectively (complete n = 21; F(2,40) = 2.07, p = 0.140, partial eta squared = 0.094). The Vibrotactile-Control sleep-only difference was –2.67 bpm (raw p = 0.070, Holm-adjusted p = 0.210, dz = –0.42). The final-minus-first 10-min change was –5.40, –3.95, and –5.59 bpm, respectively (complete n = 21; F(2,40) = 0.93, p = 0.404, partial eta squared = 0.044). None of the three Holm-adjusted pairwise comparisons was statistically significant (all adjusted p >= 0.601).

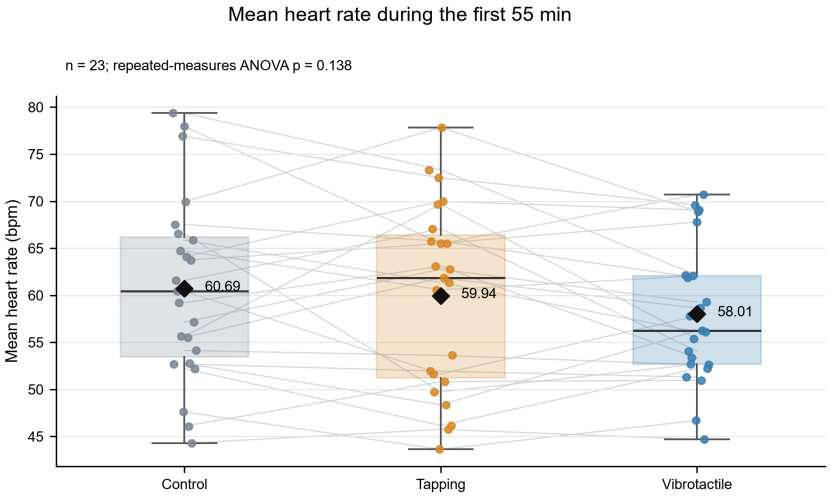


Figure 3: Participant-level mean HR during the first 55 min. Gray lines connect each participant across conditions, colored points show condition observations, black diamonds show means, and boxes show the interquartile range. The repeated-measures ANOVA was not significant (p = 0.138).

Sleep Stage Distribution

Total sleep time averaged 36.59 min in Control, 31.37 min during Tapping, and 34.98 min during Vibrotactile stimulation. Wakefulness occupied 33.45%, 42.93%, and 36.40% of scored epochs, respectively. The corresponding values were 21.12%, 17.96%, and 17.15% for N1; 17.95%, 19.77%, and 19.84% for N2; and 8.85%, 4.24%, and 5.45% for REM. None of these stage proportions showed a significant three-condition difference.

Mean N3 proportion was 18.62% in Control, 15.10% during Tapping, and 21.15% during Vibrotactile stimulation (Figure 4). The Friedman test was not significant, chi-square(2) = 0.47, p = 0.791, Kendall's W = 0.010. Numerically, the mean N3 proportion was approximately 2.5 percentage points higher during Vibrotactile stimulation than in Control and 6.05 points higher than during Tapping.

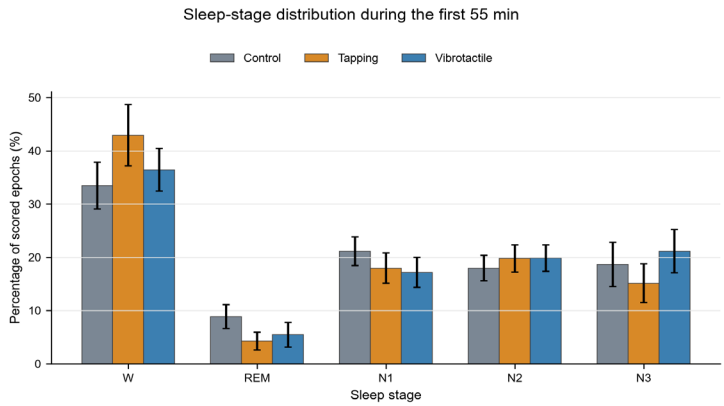


Figure 4: Mean sleep-stage proportions during the first 55 min (n = 23). Error bars show the standard error of the mean. No stage proportion differed significantly across conditions by Friedman test.

Sleep and Stage Latencies

Mean sleep-onset latency was 7.57 min in Control, 8.54 min during Tapping, and 6.61 min during Vibrotactile stimulation. The overall difference was not significant (Friedman $p = 0.170$). Sustained-sleep latency was 8.17, 9.54, and 8.35 min, respectively ($p = 0.085$).

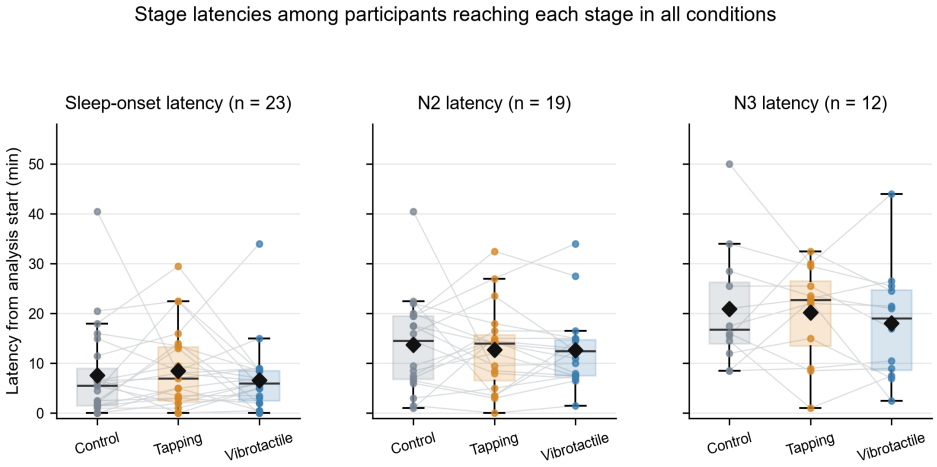


Figure 5: Paired distributions of sleep-onset, N2, and N3 latency among participants who reached the target stage in all three conditions. Gray lines connect participants across conditions and black diamonds show means. Sample sizes were 23, 19, and 12, respectively. No 55-min endpoint values were substituted for an unobserved stage.

N2 was reached by 22 of 23 participants in Control, 20 in Tapping, and all 23 in Vibrotactile stimulation. N3 was reached by 18, 15, and 18 participants, respectively. Among the 19 participants who reached N2 in

all three conditions, mean N2 latency was 13.68, 12.76, and 12.61 min (Friedman $p = 0.771$). Among the 12 participants who reached N3 in all three conditions, mean N3 latency was 20.96, 20.17, and 18.04 min ($p = 0.563$). Pairwise Wilcoxon tests for these latency outcomes were also nonsignificant after Holm adjustment.

Table 1 presents stage-attainment counts and latency summaries. Latencies were calculated only for participants who reached the respective stage within the 55-min analysis window; therefore, the number of participants differed across latency outcomes.

Table 1: Sleep-stage, stage-attainment, and latency outcomes during the first 55 min.

Outcome	Control	Tapping	Vibrotactile	Friedman p
Total sleep time (min)	36.59 (11.57)	31.37 (15.13)	34.98 (10.53)	0.840
Wake (% of epochs)	33.45 (21.03)	42.93 (27.53)	36.40 (19.14)	0.840
N3 (% of epochs)	18.62 (19.83)	15.10 (17.51)	21.15 (19.38)	0.791
Sleep-onset latency (min)	7.57 (9.42)	8.54 (8.08)	6.61 (7.00)	0.170
Reached N2, n/23	22/23	20/23	23/23	—
N2 latency (min), n = 19	13.68 (9.63)	12.76 (8.52)	12.61 (7.49)	0.771
Reached N3, n/23	18/23	15/23	18/23	—
N3 latency (min), n = 12	20.96 (12.02)	20.17 (9.76)	18.04 (11.59)	0.563

Note. Values are mean (SD) unless otherwise indicated. Stage proportions and attainment counts use the full cohort (n = 23). N2 and N3 latency means use participants who reached the target stage in all three conditions (n = 19 and n = 12, respectively). No pairwise sleep comparison was significant after Holm adjustment.

DISCUSSION

Principal Findings

The two pillow-stimulation patterns showed different numerical cardiac and sleep-stage profiles. Vibrotactile stimulation had the lowest 55-min and sleep-only mean HR, the highest N3 proportion, and the shortest complete-case mean N3 latency. Tapping did not provide clear evidence of reduced HR or facilitated sleep initiation. The overall condition tests and Holm-adjusted comparisons were nonsignificant.

Vibrotactile Stimulation

In the unadjusted comparison, Vibrotactile stimulation had a 55-min mean HR 2.69 bpm lower than Control ($dz = -0.43$), but this difference was not significant after Holm adjustment. The sleep-only HR difference was similar (–2.67 bpm). The final-minus-first 10-min change did not differ across conditions. The higher N3 proportion and shorter mean N3 latency were numerical patterns related to deeper NREM sleep, accompanied by a higher wake proportion and longer sustained-sleep latency than Control.

Whole-body rocking studies reported a shorter transition to N2 and changes in sleep oscillations (Bayer et al., 2011), and increased N3 sleep (Perrault et al., 2019). Inspired by these findings, we presented a 50-Hz pillow vibration whose amplitude varied at 0.25 Hz, in place of whole-body movement. The numerical N3 proportion and latency patterns motivate further evaluation of the relationship between stimulus intensity and sleep progression during localized pillow stimulation.

In medium-intensity rocking versus control, van Sluijs et al. (2020) reported faster delta buildup without significant changes in sleep-stage proportions or latency. Pillow stimulation likewise requires assessment of cardiac responses, sleep depth and continuity.

Tapping Stimulation

Tapping at 45 bpm targeted lower HR and earlier sleep entry, but the HR difference from Control was small and nonsignificant (–0.76 bpm). Sleep-onset and sustained-sleep latencies were approximately 1 min and 1.4 min longer, respectively, with shorter total sleep time and more wakefulness. Thus, 45-bpm Tapping provided no clear evidence of reduced HR or facilitated sleep initiation.

Human Factors Implications

Pillow interfaces can present rhythmic stimulation without whole-body displacement. Their evaluation should combine HR, sleep depth and continuity with subjective comfort, acoustic salience and usability.

Limitations

This study evaluated the first 55 min of daytime naps in a modest sample (n = 23), without assessing nighttime sleep, habitual use or next-day outcomes. Latency comparisons included only participants reaching the respective stage in all three conditions (N2: n = 19; N3: n = 12). The numerically shorter mean N3 latency reflects this N3 subset and should be considered alongside attainment counts for all 23 participants.

Prior-night sleep was not objectively verified. Calibrated displacement or acceleration amplitudes and sound-pressure levels were unavailable. The stimuli included sound and mechanical vibration, whose individual contributions were not separately evaluated.

CONCLUSION

In 23 participants over 55 min, Vibrotactile stimulation showed numerically lower HR and higher N3 proportions, with earlier mean N3 onset among participants reaching N3 in all conditions. Tapping showed slightly lower HR without earlier sleep onset. Condition tests and Holm-adjusted comparisons were nonsignificant. Prespecified follow-up should use calibrated stimuli and stage-attainment-aware latency analysis.

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