Closed-Loop Rhythmic Haptic Biofeedback via Smartwatch for Relaxation and Sleep Onset

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Abstract

We investigate the use of musically structured, closed-loop vibration patterns as a passive biofeedback intervention for relaxation and sleep initiation. By encoding rhythmic meter structures into smartwatch vibrations and adapting their frequency to be slightly slower than the user's real-time heart rate, our system aims to reduce arousal through tactile entrainment, offering a non-invasive alternative to auditory or open-loop approaches previously used in sleep and anxiety contexts. In the first study (N=20), we compared five adaptive vibration rhythms for their effects on heart rate and subjective perceptions of relaxation in a resting context. In the second study (N=28), we evaluated the most promising pattern from Study 1 in a prolonged sleep initiation setting. Results showed increased parasympathetic activity and perceived relaxation during short-term stimulation, but no significant effects on sleep-related measures during the sleep onset phase. This work contributes to the understanding of how wearable haptic feedback can support relaxation and sleep, offering design insights and identifying methodological considerations for effectively integrating haptic interaction into self-directed interventions.

CCS Concepts

• **Human-centered computing → Empirical studies in ubiquitous and mobile computing**.

Keywords

Wearable Haptics; Smartwatch Applications; Haptic Biofeedback; Rhythmic Vibration; Affective Computing; Relaxation Interventions; Sleep Initiation Support

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1 Introduction

Achieving restful sleep is essential for maintaining overall well-being, yet difficulties in falling asleep and attaining relaxation remain pervasive challenges [1–3]. Disruptions to natural sleep onset are often influenced by factors such as heightened psychological tension [4]. Stress-related physiological responses can interfere with the body's ability to smoothly transition into sleep [5, 6] and are strongly associated with prolonged sleep latency and fragmented sleep [7, 8]. Promoting sleep for a healthy lifestyle involves recognizing it as a modifiable behavior that can be enhanced through supportive, non-invasive techniques [9].

Wearable haptic interventions have recently emerged as a promising method for mitigating everyday stress with the widespread integration of vibration feedback in mobile technologies [10, 11]. Unlike visual or auditory cues, haptic feedback can directly influence affective physiological states through non-cognitive pathways, enabling immediate emotional modulation with minimal cognitive effort [12–14], referred to as "passive intervention" [15]. In particular, haptic biofeedback modulates physiological states by leveraging real-time bodily signal, enabling pre-conscious emotion regulation [16–18]. Prior biofeedback researchers using wearable haptics has demonstrated effectiveness in implicit down-regulation of physiological arousal and enhancing physiological synchrony [19, 20].

To further support relaxation at sleep onset, we draw on a modality long associated with calming physiological effects: music. Lullabies, in particular, exhibit features such as slow tempos, regular meters (often 2/4 or 3/4), legato articulation, and repetitive phrasing [21, 22], consistently identified in computational analyses of sleep-related music [23, 24]. These structures are linked to reductions in arousal and heart rate, as well as modulation of stress-related biomarkers [25–27], and are thought to promote entrainment with internal rhythms like respiration and cardiac cycles [28–30].

Building on these findings, we explore how musically informed haptic rhythm patterns, modulated through closed-loop biofeedback, can serve as a passive intervention to support relaxation during the transition to sleep. This study addresses the following research gaps:

- Haptic biofeedback has been minimally explored in sleep contexts, especially for sleep onset. Prior work has primarily focused on anxiety reduction under external stressors [31–33].

- Existing approaches often use music as background audio or as an auditory biofeedback channel [34]; our system instead encodes musical meter structures directly into the haptic signal.
- Most wearable haptic systems rely on open-loop signals (e.g., fixed-frequency based heart rate modulation); in contrast, we implement a closed-loop system that adapts in real-time based on the participant's heart rates.

2 Study 1: Relaxation Effects of Haptic Patterns

In the first study, we tested five vibration pattern samples informed by lullaby characteristics and biofeedback mechanisms, comparing them to a non-vibration control condition. To support this, we developed a custom smartwatch application capable of generating rhythmic patterns and integrating heart rate sensing for dynamic biofeedback control. The effects of the patterns on relaxation and user experience were assessed through heart rate analysis, perceived arousal, vibration experience, and user preference.

2.1 Methods

2.1.1 System. We developed an Apple Watch application [35] (Figure 1) for customizing and playing vibrotactile feedback patterns in real-time biofeedback sessions. The app delivered vibration and recorded physiological data during Study 1. Vibrotactile feedback was generated using Apple's WatchKit framework and the built-in Taptic Engine to play predefined patterns [36]. Real-time heart rate data was accessed via Apple HealthKit [37] to enable adaptive stimulation. During sessions, the app retrieved the participant's heart rate and dynamically adjusted vibration frequency based on current heart rate, aiming to support adaptive entrainment and personalized relaxation. The application provided a fully guided workflow to standardize the experimental procedure. Participants were led through all study stages directly on the watch, including baseline acquisition, pattern selection, biofeedback-driven playback, and prompts for self-assessment questionnaires. This standalone interface enabled autonomous operation without researcher intervention or companion devices. All relevant data, including heart rate samples and event timestamps, were logged locally in CSV format. Upon session completion, the data were automatically transferred to the paired iPhone via the WatchConnectivity framework [38], allowing secure and efficient retrieval for analysis.

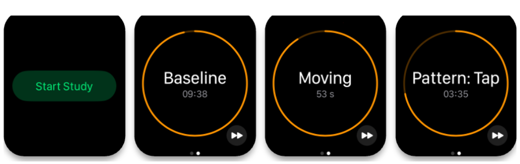

Figure 1: Screenshots of the custom Apple Watch app used in Study 1 to guide the procedure, showing interface elements for study start, baseline heart rate recording, pre-condition movement, and vibration condition.

2.1.2 Vibration Pattern Design. Five lullaby-inspired vibration rhythms were created and compared (Figure 2). Each rhythm was constructed using two types of short haptic elements as building blocks from the Apple Watch: a single tap ('Start' signal), which produces a brief, sharp vibration, and a vibration ('Failure' signal) with a slightly longer and softer tactile profile. Lullabies commonly follow time signatures such as 4/4, 2/4, or 3/4 [39]. For instance, the 3/4 time signature, also known as the waltz rhythm, is associated with a gentle, swaying motion that conveys comfort and familiarity [30].

The five rhythmic patterns were defined as follows (Figure 2):

- Tap: A sequence of regular taps in a 2/4 time signature, representing accented beats.
- Vibration: A sequence of short vibrations in a 2/4 time signature, representing unaccented beats.
- Alternating: A 2/4 time signature alternating between vibration and tap.
- 3/4: A 3/4 time signature alternating between one vibration and two taps.
- 3/4-2: A variation of the 3/4 pattern, designed as a structural counterpart.

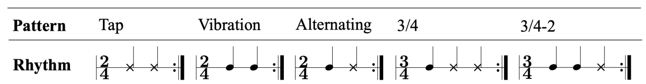

Figure 2: Five different rhythmic patterns used in Study 1. Tap elements are represented by x-shaped noteheads, and vibration elements by regular circular noteheads.

2.1.3 Biofeedback Adaptation. To reflect the principle of biofeedback, which supports users in monitoring and modulating their own physiological signals, we implemented a minimal frequency adjustment based on real-time heart rate. Evidence from a nap study suggests that heart rate biofeedback with a subtle reduction of approximately 3–5% is effective for "weak non-invasive forcing" [40, 41], where the mean of recorded heart rate of 70.38 BPM, falls within the low-tempo range (60–80 BPM), aligning with tempo characteristics commonly found in music people choose for sleep [42]. Hence, we used the 4% reduction of current heart rate to enforce physiological relaxation (configured every second). This approach contrasts with previous passive haptic biofeedback contexts, such as anxiety mitigation, where larger frequency adjustments (20–30%) are often used while participants are engaged in cognitively demanding foreground tasks [32, 33], justifying a stronger entrainment strategy.

2.1.4 Procedure. In a within-subject design, a total of 20 healthy participants (15 males, 5 females; age M=27.65, SD=10.69) assessed five vibration patterns (Figure 2). The study was conducted in a controlled environment, where participants sat at a table. Informed consent was obtained from all participants following a briefing on the study's procedures and objectives. The study procedure is outlined in Figure 3.

At the beginning of the study, participants wore an Apple Watch (SE 2, 40mm) and configured the custom app with a participant ID. Participants completed a ten-minute baseline using the smartwatch while engaging in light reading, with the final five minutes used for analysis to ensure heart rate stabilization [43]. They then completed the Stanford Sleepiness Scale (SSS) for arousal assessment,

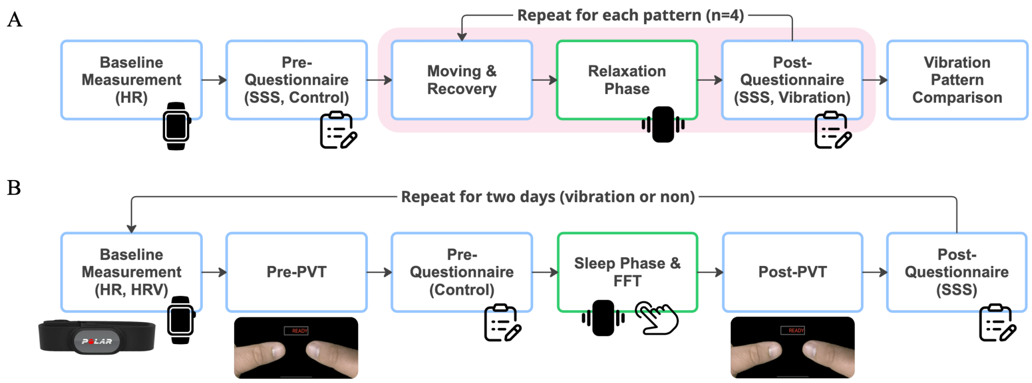

Figure 3: Overview of the procedures for (A) Study 1 and (B) Study 2

ranging from "feeling active" or "wide awake" to "sleep onset soon" [44, 45], and reported recent tobacco and caffeine intake as control factors. Participants subsequently experienced five vibration patterns in Latin square design to control for order effects. Before each condition, they walked slowly for one minute followed by a one-minute recovery to standardize pre-condition activity and reduce carryover effects. Each pattern was presented for five minutes to balance study duration and response quality [46]. Heart rate was recorded throughout using the same smartwatch that delivered the vibrations [47]. After each condition, participants completed a questionnaire evaluating the vibration's effects on relaxation (*comfort*, *relaxation*, *sleepiness*) and ambience (*recognizability*, *choppiness*), using a five-point Likert scale. After all exposures, participants ranked the patterns by relaxation suitability and provided open feedback. Snacks were offered as appreciation.

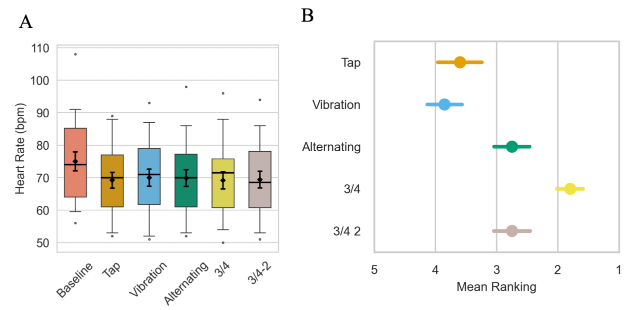

Figure 4: (A) Median heart rate across conditions. Overlaid point markers represent means with standard errors. (B) Preference rankings of vibration conditions (1 = most preferred).

2.2 Results

We used a Friedman test to evaluate differences across multiple conditions, with Wilcoxon signed-rank tests as post-hoc pairwise comparisons. A significance level of α=0.05 was used for all statistical tests.

The evaluation revealed consistent trends in physiological, perceptual, and preference measures Figure 4. All vibration patterns significantly reduced heart rate compared to baseline, although their effects were largely comparable. While subjective arousal levels did not differ significantly across patterns, perceived relaxation favored the 3/4 and Alternating rhythms. Monotonous patterns, particularly those with identical consecutive patterns such as Tap and Vibration were perceived as less pleasant. Although not statistically significant, Tap and Vibration consistently received lower ratings, suggesting they were perceived as less comfortable and more choppy. Preference rankings further confirmed the positive reception of the 3/4 pattern, which emerged as the most favored among participants.

2.2.1 Heart Rate. A Friedman test on the median heart rate values revealed a significant difference between conditions (χ^2=27.172, p<.001; Figure 4). Post-hoc Wilcoxon signed-rank tests showed that all vibration patterns significantly reduced heart rate compared to the baseline: 3/4 (p<.001), 3/4-2 (p<.001), Alternating (p<.01), Tap (p<.001), and Vibration (p<.01). No significant differences were found between the vibration patterns themselves.

2.2.2 Perceived Arousal. Subjective arousal, assessed using the Stanford Sleepiness Scale (SSS), did not differ significantly between patterns according to a Friedman test (p=.12), with mean ratings ranging from 3.10 (Baseline) to 3.65 (Alternating), corresponding to feeling "awake, but relaxed; responsive but not fully alert".

2.2.3 Vibration Questionnaire. A Friedman test revealed a significant difference in perceived relaxation between patterns (χ^2=20.04, p<.001; Figure 5). Post-hoc Wilcoxon signed-rank tests showed that 3/4 and Alternating (M=3.55, M=3.50) were rated significantly more relaxing than Tap (M=2.40; both p<.05) and Vibration (M=2.55; both p<.05). No other items showed significant differences between patterns: sleepiness (χ^2=7.88, p=.1), comfort (χ^2=4.01, p=.40), recognizability (χ^2=8.35, p=.08), and choppiness (χ^2=5.92, p=.21).

2.2.4 Preference Ranking. A Friedman test on the ranking data revealed a significant difference between patterns (χ^2=19.37, p<.01). Post-hoc Wilcoxon tests showed that 3/4 was ranked significantly higher than all other patterns, including Tap and Vibration (p<.01, p<.001), as well as Alternating and 3/4-2 (both p<.05). The 3/4 pattern was most frequently ranked first, selected by 50% of participants, reinforcing its positive reception in the questionnaire evaluation. The 3/4-2 and Alternating patterns followed, each chosen as the top preference by 25%.

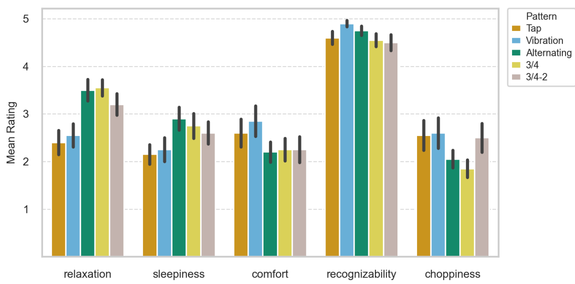

Figure 5: Mean ratings of vibration experiences across vibration patterns

3 Study 2: Single Pattern Effects on Relaxation and Sleep Onset

In the second study, we examined the prolonged effects of musically informed vibrotactile biofeedback, based on Study 1, on extended relaxation and sleep onset. In Study 1, the 3/4 pattern was rated most positively for relaxation and user preference, while reducing heart rate to a comparable extent as the other vibration patterns. Based on these findings, we tested this pattern in a longer experimental session, during which participants attempted to sleep with or without vibration. Relaxation measures (heart rate, heart rate variability, perceived arousal) and sleep induction metrics (sleep onset, psychomotor performance) were analyzed.

3.1 Methods

3.1.1 System. Study 2 used an extended version of the Apple Watch application from Study 1 (Section 2.1.1), which continued to deliver rhythmic biofeedback-based vibration and autonomously guided the procedure. To support the protocol, a custom iPhone app was introduced. It administered the Finger Tapping Task (FTT), recorded tap events with precise timestamps, and established a Bluetooth Low Energy (BLE) connection to a Polar H9 chest strap for continuous electrocardiogram (ECG) recording. All physiological data were logged locally in CSV format for later analysis. To minimize disruption during sleep onset, the smartphone display remained off throughout the sleep phase, presenting no visual stimuli. A scheduled auditory alarm gently woke participants at the end of the session. A Psychomotor Vigilance Test (PVT) [45] was conducted using the NASA-PVT iOS application [48] on an iPad Mini tablet, which recorded reaction times to visual stimuli through continuous screen-tapping input.

3.1.2 Procedure. A within-subject study was conducted with 28 healthy participants (18 males, 10 females; age M=24.79, SD=6.30) in a controlled environment furnished with a couch and a table with chairs. Each session included a 20-minute sleep phase and was scheduled between 4–8 PM to minimize disruption to participants' natural sleep rhythms and ensure consistency across varying individual sleep schedules [49]. All participants completed both conditions (with and without vibrotactile stimulation) on two separate days to prevent carryover effects. The order of conditions was counterbalanced. The study procedure is summarized in Figure 3.

Participants provided informed consent and were equipped with an Apple Watch and a Polar H9 chest strap [50] to continuously record ECG data for heart rate and heart rate variability. After configuring the custom iPhone application, a 10-minute baseline period followed, during which participants engaged in light reading, as in Study 1. They then completed a 5-minute baseline PVT [51]. Participants also filled out the Stanford Sleepiness Scale (SSS) [44] to assess subjective arousal, and a control questionnaire covering sleep habits, stimulant use, physical activity, and meal timing. In the sleep phase, participants lay on a couch with eyes closed for 20 minutes to relax and fall asleep, modeled after the Multiple Sleep Latency Test (MSLT) [52]. During this period, the 3/4 vibrotactile pattern was delivered via the Apple Watch. Following the sleep phase, participants completed a second PVT and post-study SSS to assess changes in alertness and subjective arousal. Snacks were offered as a token of appreciation upon completion.

3.1.3 Measures and Analysis. To evaluate the effects of rhythmic biofeedback vibration on relaxation and sleep onset, we collected physiological, behavioral, and subjective measures. In addition to the SSS ratings [44], ECG data from the Polar H9 provided heart rate and heart rate variability, which were analyzed in both the time domain (RMSSD) [53, 54] and frequency domain—high-frequency (HF, 0.15–0.4 Hz) and low-frequency (LF, 0.04–0.15 Hz) components, and the LF/HF ratio [55]—to assess autonomic nervous system activity [53, 56, 57]. HR and frequency-domain HRV were analyzed as change from baseline of the recorded day to control for individual differences, while RMSSD was directly compared due to its stability in absolute terms [58, 59]. SOL, defined as the time until the first tapping interval exceeds 8 seconds [60], was derived from the FTT that recorded inter-tapping intervals (ITI) as behavioral indicators of sleepiness [60–62]. These measures have been shown to correlate with EEG-based markers distinguishing wakefulness from stage 1 sleep [62]. Alertness was assessed using the PVT [51], with key metrics including reaction time, lapses (missed responses or responses >500 ms), false starts, and errors [63]. Prior research has shown that drowsiness significantly slows reaction times and increases omission errors [64].

3.2 Results

The same statistical approaches as in Study 1 were applied, including the Friedman test and Wilcoxon signed-rank tests, with a significance level of α=0.05. Of the initial 28 participants, three of them were excluded from the analysis due to unusually sudden high HR spikes observed during the sleep phase.

Heart rate variability (HRV) measures, i.e., RMSSD and HF power, showed trends suggestive of increased parasympathetic activity during the vibration condition, while no statistically significant differences were observed between the vibration and control conditions in heart rate, HRV, perceived arousal, sleep onset latency, or psychomotor performance. Cognitive and behavioral outcomes remained consistent across conditions.

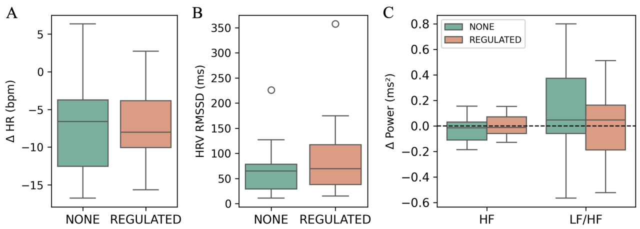

Figure 6: Physiological indicators of autonomic activity in vibration ("regulated") and control ("none") conditions: (A) Heart rate difference from baseline, (B) RMSSD (time-domain HRV), and (C) HF and LF/HF ratio (frequency-domain HRV) differences from baseline. Higher RMSSD and HF, and lower LF/HF values reflect increased parasympathetic activity.

3.2.1 Heart Rate and Heart Rate Variability. A Wilcoxon signed-rank test on median heart rate differences (from baseline to sleep phase) between the 3/4 vibration condition and the control condition revealed no significant effect (W=175.00, p=.75). A main effect on RMSSD was not statistically significant, although the Wilcoxon signed-rank test indicated a trend toward increased parasympathetic activity with the 3/4 vibration pattern compared to baseline (W=104, p=.07). In the frequency domain analysis of HRV, no significant differences were found between conditions in the HF band (W=128.00, p=.24) or the LF/HF ratio (W=141.00, p=.39). While not statistically significant, both measures showed trends consistent with increased parasympathetic activity during the sleep phase, as indicated by a tendency toward higher HF power and a lower LF/HF ratio under vibration feedback.

3.2.2 Cognitive and Behavioral Outcomes. No significant differences were observed between the 3/4 vibration and control conditions in cognitive or behavioral measures. Subjective arousal ratings on the SSS did not differ between conditions (p=.13). Sleep onset latency (SOL), derived from the FTT, showed no significant difference across conditions (p=.82), with no observable different across two days (p=.46). Psychomotor performance, assessed using the PVT, revealed no significant differences in reaction time (p=.15), number of errors (p=.41), lapses (p=.25), or false starts (p=.11).

4 Discussion

The results indicate that biofeedback-based rhythmic vibration patterns effectively reduced heart rate and were perceived as relaxing, suggesting potential for acute physiological and subjective calming effects. However, when the most promising pattern was tested in a prolonged sleep initiation context, no statistically significant effects were observed across physiological, behavioral, or subjective measures. This discrepancy suggests that while rhythmic haptic feedback may support momentary relaxation, its influence on longer-term outcomes such as sleep onset may be limited, or may require extended exposure, individual adaptation, or multimodal integration.

In Study 1, all vibration patterns led to heart rate reduction, but those with rhythmic variation—namely, 3/4 and Alternating—were rated more positively in terms of relaxation and user preference. In contrast, monotonous patterns such as Tap and Vibration were consistently rated as less relaxing, indicating that repetitive, unvaried feedback may be less effective in creating a pleasant or calming experience. Although no significant effects were found for comfort, it is noteworthy that alternating patterns (Alternating, 3/4, 3/4-2) were rated as more relaxing and sleep-inducing while also being perceived as less choppy. This suggests that simpler rhythms with shorter bursts may be experienced as more comfortable, but not necessarily more calming. High recognizability ratings across patterns may indicate a need to reduce perceptual salience in future designs. Unobtrusive feedback could help differentiate physiological responses and subjective arousal levels. Future studies may benefit from integrating minimally invasive sleep detection methods to further reduce interference with haptic feedback during sleep attempts.

In Study 2, the 3/4 vibration pattern did not yield statistically significant effects across measured outcomes, though trends in RMSSD and HF power—both indicators of vagal activity—suggested potential parasympathetic activation. While these effects were not robust enough to influence overt sleep initiation or behavioral alertness in a single session, they warrant further exploration in larger or longer-term studies to determine cumulative or individualized effects. Notably, the significant heart rate reduction observed in Study 1 may indicate that shorter stimulation durations (e.g., 5 minutes) are more effective, while extended exposure may attenuate the relaxation response or induce overstimulation. As one participant noted, "The vibration rhythm made me tired, but at a certain point, it could have stopped, as it seemed to keep me awake a little longer." This suggests that a 20-minute stimulation period might not have been ideal for sleep initiation, and future studies should explore shorter or adaptive durations. In addition, some participants reported that the rhythmic feedback during the Finger Tapping Task (FTT) increased cognitive load, interfering with their ability to maintain a "personal rhythm" and potentially hindering sleep onset [65]. This implies that dynamic patterns may conflict with internal rhythms and inadvertently induce cognitive stress when paired with tasks during sleep initiation. Although not statistically significant, the vibration condition showed shorter reaction times (11.55 ms vs. 18.70 ms), fewer lapses, and fewer false starts compared to the control, suggesting a potential increase in alertness, possibly due to greater cognitive engagement.

Usage Contexts and Situational Moderators. Some participants noted that the vibrations were distracting due to associations with smartwatch notifications or alarm functions. In Study 2, 19 participants reported not regularly using a smartwatch with haptic feedback. Among these non-regular users, vibration exposure was associated with a greater increase in HF power and a slight reduction in heart rate compared to baseline. Furthermore, the vibration condition appeared to mitigate declines in cognitive performance, with more pronounced effects observed in this subgroup. These observations suggest that habitual smartwatch use may influence the perceived and physiological effectiveness of haptic feedback. Future studies should consider smartwatch usage as a potential moderating factor, accounting for both habituation effects and the influence of wrist-based placement. An exploratory analysis including caffeine consumption as a covariate in linear mixed-effects models suggested a non-significant trend toward reduced sleep duration when caffeine was consumed closer to bedtime (p=0.18). Future studies with larger samples may help clarify the impact of such confounding factors, accounting for individual variability in sleep and relaxation responses. The First Night Effect (FNE), characterized by increased alertness and reduced sleep quality on the first night in unfamiliar environments [66–68], may have contributed to the non-significant results in this study, despite the randomization of study nights. Future research could include a buffer day to mitigate FNE and ensure more stable baseline sleep behavior.

Extending the Dimensions of Wearable Haptic Interaction. Our findings partially align with those of Choi et al. [40], who demonstrated significant HRV effects from closed-loop vibration feedback during full sleep cycles using a woofer embedded under a mattress. In contrast to our direct-contact smartwatch-based stimulation, their setup provided indirect vibrations, which may have been less intrusive. To reduce potential disturbance from direct skin contact, future work could personalize vibration intensity or explore alternative tactile modalities such as soft-touch actuation, which more closely resembles gentle human touch and may mitigate associations between vibrations and alert functions [69–73]. Building on Choi et al.'s design, future studies might also examine alternative body locations—such as the back or head—that are more closely associated with rest, potentially enhancing the effectiveness of haptic interventions.

Clarifying the Role of Adaptivity and Individual Sensitivities. While this study employed closed-loop vibration synchronized to real-time heart rate, the effects of open-loop rhythmic stimulation in wakeful relaxation remain largely unexplored and were not directly compared here. It remains unclear whether physiological entrainment provides added benefits over fixed-frequency rhythms, or whether perceived relaxation stems primarily from rhythm structure or tempo. Future studies should compare adaptive and static designs to isolate the value of synchronization. Additionally, individual responses to rhythmic patterns, particularly the preferred 3/4 and Alternating structures, may depend on musical familiarity or cultural background. Such factors could influence both subjective perception and physiological impact, and should be assessed or controlled for in future personalized interventions.

5 Future Work

Based on the findings and study design insights, several directions emerge for future research. First, the absence of significant long-term effects despite acute heart rate reductions suggests the need to explore adaptive or time-limited stimulation protocols that optimize relaxation without risking overstimulation during extended exposure. Second, the influence of user familiarity with wearable haptics should be examined more systematically to account for habituation or alert associations, which may moderate the effectiveness of vibrotactile feedback. Third, future work should also compare closed-loop and open-loop designs to assess whether physiological synchronization yields benefits beyond rhythm perception alone, while accounting for individual or cultural differences in rhythm sensitivity. Fourth, the study design could be refined by including a buffer day to mitigate the First Night Effect (FNE), thus ensuring more stable and representative baseline sleep behavior. Finally, future work can investigate alternative haptic modalities or body locations that align more naturally with sleep and rest (e.g., soft-touch feedback or stimulation at the back or head), potentially improving perceptual comfort.

6 Conclusion

This study examined rhythmic, biofeedback-driven vibrotactile patterns delivered via a smartwatch as a passive intervention for relaxation and sleep initiation. The first study demonstrated significant effects of brief stimulation on heart rate and perceived relaxation. The second study showed that heart rate variability trends indicated increased parasympathetic activity, although no significant effects were found in the prolonged sleep initiation context. This suggests that while rhythmic haptics may support momentary relaxation, their translation to sleep-specific outcomes requires further refinement. Our method addresses a gap in prior research by introducing sleep-related, biofeedback-driven haptics using commercially available wearables, compared to existing auditory or open-loop approaches. Future research should refine physiological and subjective markers to distinguish relaxation from sleepiness, refine stimulation timing and modality, explore alternative haptic patterns and body sites, and use larger, longitudinal designs to better understand individual responsiveness and cumulative effects in real-world sleep hygiene applications.

Acknowledgments

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