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Design of Pseudo-Heartbeat Auditory Feedback for Enhancing Interoception in a Meditation Support System
(Reka Bentuk Maklum Balas Auditori Denyutan Jantung Pseudo bagi Meningkatkan Interosepsi dalam Sistem Sokongan Meditasi)

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ABSTRACT

Meditation has been reported to improve subjective sleep quality and has received attention in the context of Cognitive Behavioral Therapy for Insomnia (CBT-I). In this study, we aim to establish design guidelines for a meditation support system that utilizes “pseudo-heartbeat biofeedback” based on predictive coding theory. This system is designed to induce a subjective meditative state and promote sleep. Specifically, we propose that presenting heartbeat sounds at rates set to a fixed percentage below the user’s actual heart rate may enhance interoception and evoke the subjective experience of a decrease in heart rate, which is conducive to a meditative state. To evaluate this approach, we conducted an experiment with 120 participants using the interactive artwork “TAI-ON,” exhibited at the Art Gallery of SIGGRAPH Asia 2024 (December 4 - 6, 2024). In a quiet and focused environment, participants were randomly assigned to one of four groups receiving pseudo-heartbeat sounds at manipulation rates of 0%, −10%, −20%, or −30% relative to their actual heart rate. A non-contact sensor measured actual heart rates, while pre- and post-experience questionnaires assessed the participants’ meditative state, perceived decrease in heart rate, and sleepiness. Our findings indicate that higher manipulation rates were associated with a stronger tendency to perceive a decrease in heart rate. Conversely, only the group receiving unmanipulated feedback (0% manipulation) tended to feel that the heartbeat sounds matched their own heartbeat. These subjective evaluations offer clear design implications for meditation support systems using pseudo-heartbeat feedback, elucidating both the potential and the limitations of leveraging interoceptive illusions.

Keywords: Meditation, Interoception, Auditory Biofeedback, Pseudo-Heartbeat Biofeedback, Cognitive Behavioral Therapy for Insomnia (CBT-I)

ABSTRAK

Meditasi telah dilaporkan dapat meningkatkan kualiti tidur subjektif dan telah mendapat perhatian dalam konteks Terapi Tingkah Laku Kognitif untuk Insomnia (CBT-I). Dalam kajian ini, kami bertujuan untuk mewujudkan garis panduan reka bentuk untuk sistem sokongan meditasi yang menggunakan "maklum balas bio degupan jantung pseudo" (pseudo-heartbeat biofeedback) berdasarkan teori pengekodan prediktif (predictive coding theory). Sistem ini direka bentuk untuk mendorong keadaan meditasi subjektif dan menggalakkan tidur. Secara khusus, kami mencadangkan bahawa membentangkan bunyi degupan jantung pada kadar yang ditetapkan kepada peratusan tetap di bawah kadar degupan jantung sebenar pengguna boleh meningkatkan interosepsi (interoception) dan membangkitkan pengalaman subjektif penurunan kadar degupan jantung, yang kondusif untuk keadaan meditasi. Untuk menilai pendekatan ini, kami menjalankan eksperimen dengan 120 peserta menggunakan karya seni interaktif "TAI-ON," yang dipamerkan di Galeri Seni SIGGRAPH Asia 2024 (4–6 Disember 2024). Dalam persekitaran yang sunyi dan fokus, peserta dibahagikan secara rawak kepada salah satu daripada empat kumpulan yang menerima bunyi degupan jantung pseudo pada kadar manipulasi 0%, −10%, −20%, atau −30% berbanding kadar degupan jantung sebenar mereka. Sensor bukan sentuhan mengukur kadar degupan jantung sebenar, sementara soal selidik pra- dan pasca-pengalaman menilai keadaan meditasi peserta, tanggapan terhadap penurunan kadar degupan jantung, dan rasa mengantuk. Penemuan kami menunjukkan bahawa kadar manipulasi yang lebih tinggi dikaitkan dengan kecenderungan yang lebih kuat untuk merasai penurunan kadar degupan jantung secara subjektif. Sebaliknya, hanya kumpulan yang menerima maklum balas tanpa manipulasi (manipulasi 0%) cenderung merasakan bahawa bunyi degupan jantung sepadan dengan degupan jantung mereka *sendiri. Penilaian subjektif ini menawarkan implikasi reka bentuk yang jelas untuk sistem sokongan meditasi yang menggunakan maklum balas degupan jantung pseudo, menjelaskan kedua-dua potensi dan batasan dalam memanfaatkan ilusi interoseptif.*

Kata Kunci: Meditasi; Interosepsi; Biofeedback Auditori; Biofeedback Denyutan Jantung Pseudo; Terapi Tingkah Laku Kognitif untuk Insomnia (CBT-I)

INTRODUCTION

Roughly one in ten people worldwide suffer from insomnia, identifying it as the most prevalent sleep pathology [1]. This disorder extends beyond diminishing daily functioning and well-being; it acts as a precursor to various physical and mental health comorbidities [2]. While Cognitive Behavioral Therapy for Insomnia (CBT-I) is widely advocated as the primary intervention [3], its implementation faces structural barriers, including a scarcity of specialists and the substantial financial strain it places on healthcare systems, often resulting in reliance on pharmacological alternatives [4]. Consequently, current therapeutic frameworks face significant societal challenges.

To address these limitations, our research turns to meditation, a practice rooted in Eastern traditions designed to anchor the mind in the immediate moment, which has proven effective for enhancing subjective sleep quality [5],[6]. This practice is closely linked to interoception-the awareness of internal somatic signals-and is frequently integrated into wellness technologies [7], [8]. By fostering a mental state that disconnects from thoughts unrelated to somatic awareness, interoception-based meditation holds particular promise for treating psychophysiological insomnia, where psychological factors are dominant [9].

We employ pseudo-heartbeat biofeedback as an engineering method to facilitate this process. Biofeedback utilizes operant conditioning to help individuals regulate physiological responses [10]. Specifically, pseudo-heartbeat techniques alter the auditory feedback of the heartbeat to elicit emotional changes or stress reduction, a phenomenon supported by numerous subjective evaluations [11], [30], [31] ,[32] ,[13] Given that the heartbeat is a distinct and easily perceptible physiological signal, it serves as an ideal target for systems focusing on interoceptive training.

However, adapting existing pseudo-heartbeat research to meditation presents three distinct obstacles. First, prior studies often relied on visual feedback, which risks increasing alertness and is thus unsuitable for meditation [30]. Second, findings regarding the efficacy of this biofeedback are inconsistent and highly context-dependent, lacking a unified theoretical framework [34]. Third, there is a notable absence of literature evaluating this specific biofeedback method within a meditative context, making direct application of past protocols difficult. Therefore, it is essential to engineer a non-intrusive system that naturally deepens internal focus. In response, we developed a system using pseudo-heartbeat sound feedback to enhance interoception and conducted subjective assessments to establish design guidelines for such systems.

For this verification, we utilize auditory stimuli, which are better suited for managing arousal levels during sleep-related interventions [35]. Our approach differs from fixed-tempo methods by using real-time demodulation to dynamically reflect the user's pulse, a technique shown to be more effective in facilitating state changes [36], [12]. Lowering the heart rate is theorized to activate the parasympathetic nervous system, facilitating both meditative depth [27] and the initial stages of sleep [37]. Our system creates a feedback loop that guides the heart rate downward relative to its actual pace. Given the variability in previous findings, this study seeks to validate this design specifically for the environment of sleep and meditation support.

Based on this framework, we aim to develop a system utilizing pseudo-heartbeat biofeedback to support both sleep and meditation, examining its applicability through the following research questions.

RQ#1. By listening to downward pseudo-heartbeat sounds through this system, can one perceive a subjective decrease in heart rate and the effects of meditation?

RQ#2. Through this system, can one subjectively experience the illusion that "this is my own heartbeat," and is there a threshold for the manipulation rate of the pseudo-heartbeat that induces such an illusion?

RQ#3. By listening to downward pseudo-heartbeat sounds through this system, does one's subjective arousal level decrease?

The contribution of this study lies in providing fundamental insights into the setting of manipulation rates and the design of auditory feedback for a meditation-promotion system using heartbeat sounds that employ pseudo-heartbeat biofeedback, as well as clarifying the issues that must be considered in system design to induce the illusion of interoception.

An earlier version of this study was presented as a poster at Augmented Humans 2025 [38]. The current manuscript significantly expands upon the preliminary findings by providing a comprehensive statistical analysis, including ordinal logistic regression, to deeply investigate the interactions between the manipulation rate, interoceptive illusion, and mindfulness states.

RELATED WORKS

False Heart Biofeedback

Previous research demonstrates that manipulating external heart rate feedback induces significant emotional and physiological changes. Ueoka [11] utilized tactile feedback to amplify fear responses, while Dey [12] showed that altering heart rate feedback by ±15–30% in a VR environment effectively regulated emotional levels. Similarly, Ota [13] found that auditory feedback presented 20 BPM slower than the actual heart rate reduced frustration during driving. These studies collectively suggest that creating an illusion of altered heart rate through exteroceptive stimuli- whether tactile or auditory- is an effective method for modulating user states.

Meditation System

In the context of meditation support, auditory stimuli are preferred over visual inputs to minimize distraction and support inward attention. Vidyarthi [6] proposed a system using interactive audio to facilitate "mindful inward focus," and Rusch [14] noted that mindfulness meditation improves sleep quality across various clinical populations. Consequently, a meditation-promotion system utilizing biofeedback must be

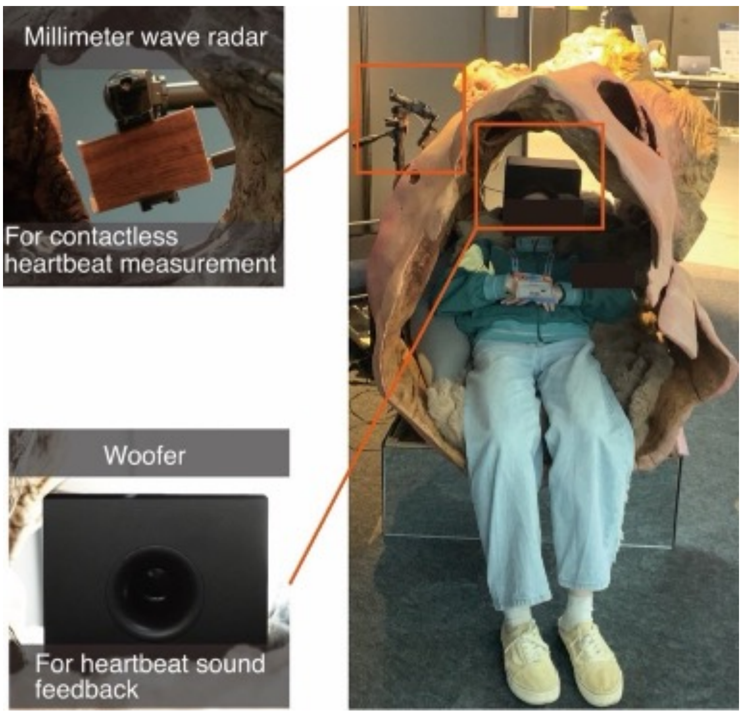

FIGURE 1. Overview of the hardware used for providing auditory feedback (left) and a demonstration of experiencing the system (right)

designed based on theoretical principles where sound intensity and rhythm support the user's inward focus rather than disrupting it.

Interoception

Interoception, the perception of internal bodily states, is central to meditation practices such as "Body Scan" \cite{dreeben2013mbsr} and "Body Awareness" [8]. Research highlights the complex interaction between interoception and exteroception: Suzuki [15] demonstrated that synchronizing external cues with heartbeats enhances the sense of body ownership, whereas Abdallah [16] reported that high external immersion (e.g., in VR) might diminish cardiac interoception. Therefore, to successfully apply pseudo-heartbeat biofeedback to meditation, the system must balance immersion with internal awareness, aiming to induce subjective synchronization that reinforces, rather than obscures, interoception.

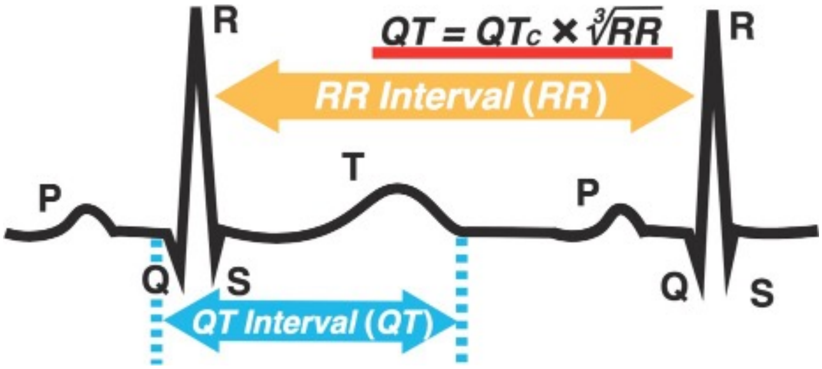

FIGURE 2. Schematic representation of the cardiac cycle defining the RR and QT intervals used for pseudo-heartbeat synthesis

METHODOLOGY

Pseudo-Heartbeat Audio Feedback System

Figure 1 illustrates the system architecture. We developed a mechanism that measures heart rate using a non-contact sensor and generates pseudo-heartbeat sounds in real time. The system analyzes the user's heart rate to calculate inter-beat intervals (Figure 2), applies a specific manipulation rate, and synthesizes realistic heartbeat sounds by convolving pre-recorded audio sources. These sounds are then output through a woofer to provide deep bass feedback.

The system reads time-series BPM data to calculate the standard inter-beat interval, RR, using Equation (1).

$$\mathrm{RR} = \frac{60}{\mathrm{BPM}} \tag{1}$$

To investigate the effects of heart rate modulation, this RR interval is adjusted by a manipulation factor N (0%, -10%, -20%, -30%) to derive the final playback interval fRR (2). This ensures the feedback rhythm continuously adapts to the user's physiological fluctuations.

$$\mathrm{fRR} = \mathrm{RR} * (100 + N) \tag{2}$$

Non-contact Sensing

We utilized a millimeter-wave radar (miRadar8, Sakura Tech [17]) as the sensing device. Millimeter waves penetrate clothing to detect subtle chest displacements, allowing for accurate non-contact heart rate estimation. The sensor was positioned outside the participant's enclosure (“TAI-ON”) to transmit measurement data via USB to a PC, where the BPM (Beats Per Minute) is dynamically updated for the feedback loop.

Physiologically Accurate Sound Synthesis

To reproduce natural heart sounds, we extracted the first (S1) and second (S2) heart sounds from actual recordings and processed them with a low-pass filter. The timing between S1 and S2 is critical for realism; thus, we employed the Fridericia correction formula [18] to dynamically determine this interval based on heart rate.

Assuming a standard corrected QT interval $QT_!$ of 0.4 seconds for healthy adults [19], the actual

QT duration is calculated as shown in Equations (3) and (4).

$$QT_c = \frac{QT}{\sqrt[3]{RR}} \quad (3)$$

$$QT = QT_c * \sqrt[3]{RR} \quad (4)$$

Playback Logic

For each beat, the system executes the following sequence:

i. Acquire the current BPM and compute the playback interval fRR.
ii. Calculate the actual QT time using the Fridericia formula.
iii. Determine the timing for S2 by subtracting a fixed QR duration (0.04 s) from QT.
iv. Play S1 at $t=0$ and S2 at t=RT.

Experiment at SIGGRAPH Asia 2024

About the exhibition work "TAI-ON"

In this study, we evaluated the proposed system in a real-world conference setting using the interactive artwork "TAI-ON" as the experimental apparatus. The work was exhibited at the Art Gallery of SIGGRAPH Asia 2024, held in Japan from December 4 to 6, 2024. A preliminary report focusing on the basic system design and initial attendee feedback at this exhibition was previously presented as a poster [38]. The installation was designed to minimize the salience of digital devices and create an environment that naturally encourages inward attention. Participants lay inside a zelkova wood structure that concealed the sensing and actuation hardware, thereby reducing extraneous cues and supporting awareness of internal bodily states [20]. Compared with a conventional laboratory, the exhibition space allowed participants to experience the system in a relatively relaxed state under the authors' supervision, offering conditions closer to everyday use. Each experience lasted approximately 4–5 minutes, and qualitative feedback frequently mentioned relaxation, drowsiness, and a sense of isolation from the outside world, as well as the soothing tactile and olfactory qualities of the wood.

Participants

A total of 120 visitors to the exhibition, aged 18 years or older and without reported hearing impairments, volunteered to participate and completed pre- and post-experience questionnaires (with some missing data). Recruitment was conducted via a brief information sheet and verbal explanations at the booth. Due to spatial and time constraints in the exhibition environment, detailed demographic information was not collected.

A power analysis using G*Power 3.1.9.2 [20], assuming a large effect size ($f = 0.4$) and a significance level of $\alpha = 0.05$ for a one-way ANOVA with a single independent variable, indicated a required sample size of 112 participants. In all analyses, samples with missing values were excluded according to the analysis target, yet the remaining sample size always exceeded 112, ensuring sufficient statistical power.

Procedure

Prior to the experiment, participants assessed their drowsiness using the bilingual Karolinska Sleepiness Scale (KSS) [21], [22]. They then removed electronic devices and lay down in the experimental apparatus "TAI-ON" to remain at rest. The session began with one minute of wind sounds for stabilization, followed by one minute of real-time biofeedback. Subsequently, participants were exposed to a pseudo-heartbeat for two minutes, manipulated at one of four rates (0%, -10%, - 20%, -30%) relative to their actual heart rate. This sequence aimed to enhance engagement through an initial fast-tempo presentation [23]. A between-subjects design was employed with the manipulation rate as the independent variable.

Measures

Post-experience, participants completed an eight-item questionnaire assessing interoception (subjective synchronization), user experience, and sleepiness (Table 1). Items utilized a 7-point Likert scale, except for the 9-point KSS. To assess short-term mindfulness specifically regarding "present-moment awareness" [25], we consolidated items from CAMS-R [26] and FMI [25] into a single question (Q7) to accommodate the time constraints of the exhibition environment. The session concluded with free-text feedback, taking approximately 10 minutes in total.

Statistical Treatment of the Data

Statistical analysis was performed using R. Given the ordinal nature of the data, non-parametric tests were applied, with bootstrapping (1,000 iterations) used for descriptive statistics. We employed Spearman's rank correlation coefficient for analyzing item relationships and ordinal logistic regression for group comparisons. The Bonferroni correction was applied to multiple comparisons to adjust *p*-values. All statistical analyses were conducted using R (version 4.5.2).

TABLE 1. The contents of the questionnaire conducted after the experience and the results of the non-parametric analysis of variance. For Item 8, the change score on the Karolinska Sleepiness Scale (KSS) (post-experiment minus pre-experiment) was used for the analysis.

Question Number	Text	scale		*p*-value
		Not at All.	at All.	
1	Did you feel that the heartbeat sound feedback was your own heartbeat?	1	7	0.08
2	Did you feel that the heartbeat sound feedback matched the rhythm of your own heartbeat?	1	7	0.232
3	Did you feel a decrease in your own heartbeat during the experience?	1	7	0.061
4	Did you feel a sense of your body or emotions being controlled by the heartbeat sound?	1	7	0.471
5	Did you feel any discomfort with the rhythm or tone of the heartbeat sound?	1	7	0.863
6	Did you feel that volume of the heartbeat sound was appropriate?	1	7	0.168
7	Were you able to focus on the present moment during the experience?	1	7	0.664
		Extremely Alert	Extremely Sleepy	
8	(KSS) Please circle the number that best corresponds to the statement describing	1	9	0.949

TABLE 2. The mean and standard deviation (represented in parentheses) of survey response scores after resampling using the bootstrap method. Arousal Level represents the change in the Karolinska sleepiness scale (KSS) scores from pre-experiment to post-experiment.

***: $p < .001$

Manipulation Rate	Question Number 1	2	3	4	5	6	7	Arousal Level
0 %	4.31 ***(0.24)	4.21 ***(0.29)	4.09 ***(0.33)	4.37 ***(0.34)	3.25 ***(0.34)	4.96*** (0.26)	5.42*** (0.36)	0.60 (0.42)
10 %	3.14 (0.41)	3.31 (0.39)	4.85*** (0.38)	4.09 *** (0.37)	2.99*** (0.41)	4.77*** (0.36)	4.96*** (0.38)	0.44 (0.47)
20 %	3.78 (0.32)	3.78 (0.25)	4.55*** (0.36)	4.06 *** (0.31)	2.94 *** (0.28)	4.54*** (0.29)	5.16*** (0.26)	0.29 (0.30)
30 %	3.56 (0.24)	3.57 (0.29)	5.47*** (0.21)	4.72 *** (0.32)	3.09*** (0.39)	5.39*** (0.30)	5.02*** (0.32)	0.30 (0.44)

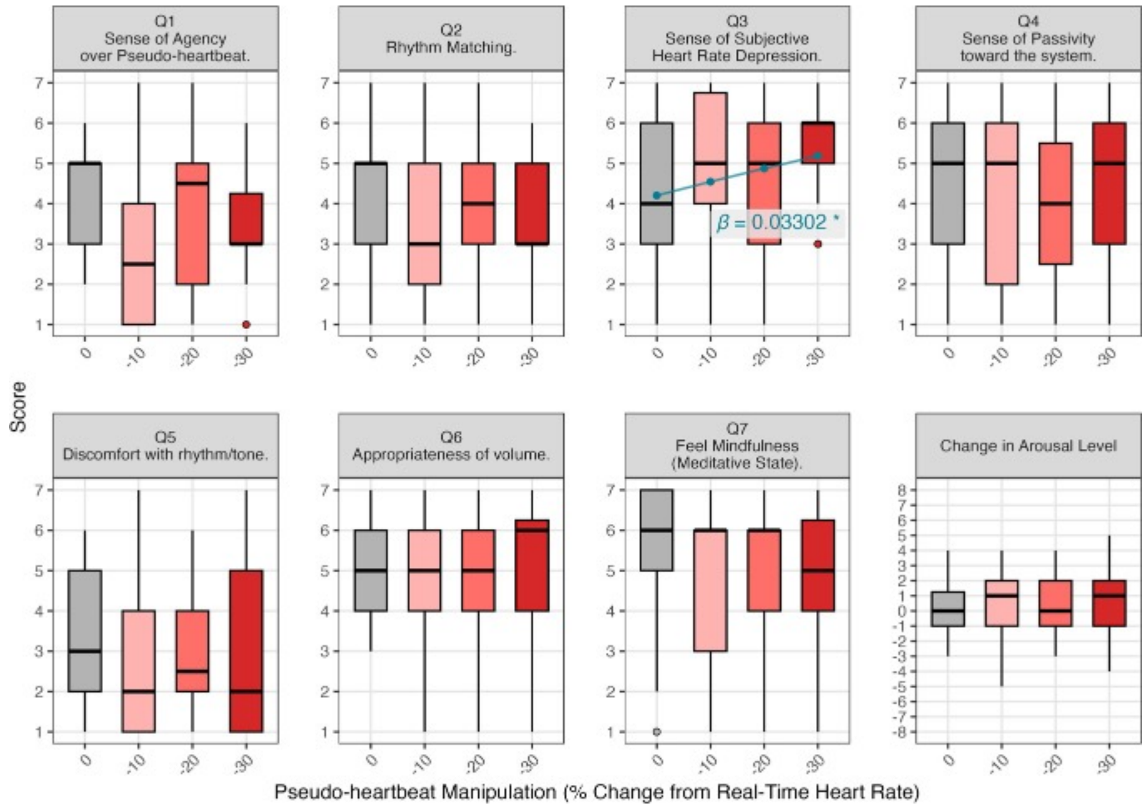

FIGURE 3. Boxplots showing questionnaire scores for each condition. The red regression curve in the figure represents the predicted results from the ordinal logistic regression model. In this model, each category boundary (Intercepts: 1|2, 2|3, …) is treated as a separate cutpoint, while the effect of the explanatory variable (rate) is captured by a single coefficient (0.03302).

RESULTS & DISCUSSION

This section integrates the analysis of subjective effects with a discussion on the system's design implications, addressing the research questions (RQ) formulated earlier.

RQ #1: Meditation Effect and Perceived Heart Rate Decrease

Initial non-parametric tests (Kruskal–Wallis) revealed no statistically significant differences in questionnaire scores across the four manipulation rate conditions (0%, -10%, -20%, -30%) (Table 1). Consequently, we employed regression analyses to explore the relationships between variables in greater depth. While the direct correlation between the meditation effect (Q7) and perceived heart rate decrease (Q3) was not statistically significant (ρ =0.28, p =0.089, Figure 3), logistic regression analysis identified a significant mutual influence. The perceived decrease in heart rate significantly predicted the mindfulness state (p =0.0122, OR =1.302), and conversely, the mindfulness state significantly predicted the perceived heart rate decrease (p =0.0086, OR =1.321). Although the main effects in Table 1 were not statistically significant-suggesting that no clear between-condition differences emerged at the level of simple group comparisons-the regression results indicate that perceived heart rate decrease and the meditation-related outcome are related when examined at the individual level. Taken together, these findings imply that the effect is less likely to manifest as a straightforward mean difference between conditions, and more likely to appear as a conditional or individual-difference–dependent association across participants.

These findings suggest that a subjective reduction in heart rate and a state of mindfulness can be induced concurrently and may reinforce each other. This aligns with reports that actual heart rate reduction correlates with mindfulness [27]. However, these tendencies occurred regardless of the specific manipulation rate. This effect may stem from two possible reasons. First, the subjective effects might have been induced by the experimental environment, such as

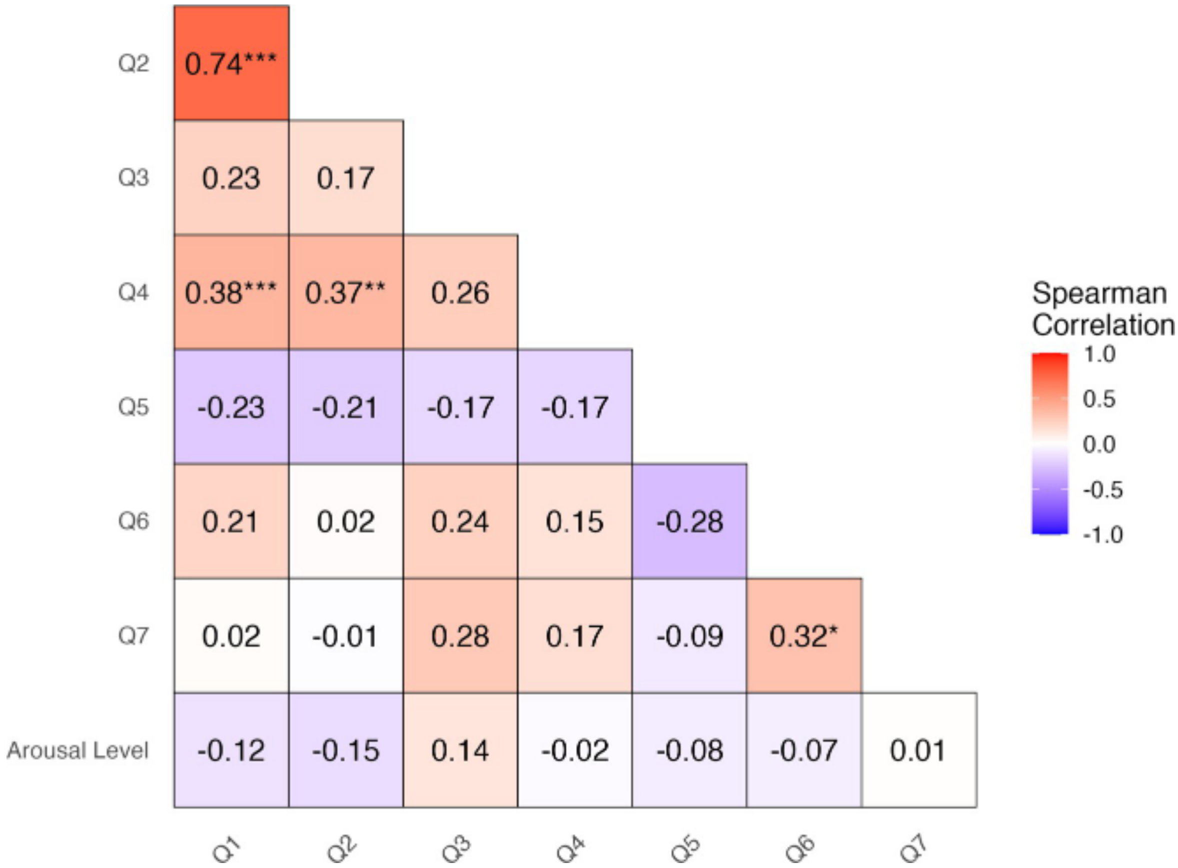

FIGURE 4. Spearman's correlation coefficients between the questionnaire item scores. Arousal Level represents the change in the Karolinska sleepiness scale (KSS) scores from pre-experiment to post-experiment. *: $p < .05$, ***: $p < .01$, ***: $p < .001$

the apparatus ("TAI-ON") and the exhibition venue, rather than the heartbeat sound itself. The specific context of the artwork-where participants are freed from digital devices and receive auditory feedback based on their own heart rate-could have influenced the results. Second, the efficacy of the heartbeat feedback may depend on individual characteristics. This is because statistical significance, which was not observed in mean-based analyses such as inter-group comparisons among the condition groups (0%, -10%, - 20%, -30%), was confirmed through ordinal logistic regression analysis (Q3, Figure 3).

Based on these findings, future research must verify the effects of this system, as suggested by the current experiment, in a controlled laboratory environment. Additionally, future work could explore algorithms to optimize the heartbeat generation parameters according to individual characteristics.

RQ #2: Interoceptive Illusion and Manipulation Rate

The results indicate that the system failed to induce a robust interoceptive illusion in the manipulated conditions. Participants significantly perceived the feedback as their own heartbeat (Q1 > 4) only in the actual heart rate condition (0%) (Table 2). This suggests that in a task-free resting state, participants can easily detect discrepancies between their internal state and external feedback, making the conditions for illusion stricter than in task-based studies [12].

Despite the lack of ownership over the sound, logistic regression revealed that the subjective sense of heart rate decrease (Q3) significantly strengthened as the manipulation rate increased (p =0.024, Figure 3). This implies a trade-off: higher manipulation rates enhance the perception of a slowing heart but diminish the illusion of ownership. Furthermore, a strong sense of external control (Q4) was observed across all conditions and correlated positively with subjective synchronization (Q1: ρ =0.38, Q2: ρ =0.37, Figure 4). Paradoxically, the more participants recognized the sound as their heartbeat, the more they felt controlled. This suggests that immersion in the system may have enhanced their cardiac interoceptive awareness. Additionally, the realistic nature of the heartbeat sound might have been too direct, suggesting that ambiguous feedback, as proposed by Vidyarthi [6], might be more effective for meditation by reducing the sensation of external control.

RQ #3: Arousal Level

Contrary to expectations, no significant changes in arousal or drowsiness (KSS) were observed across conditions (Table 1), nor were there correlations with other items. Two potential factors explain this null result. First, the absolute BPM presented varied by individual; faster baseline heart rates result in faster feedback tempos, which may induce sympathetic activation [23] rather than relaxation. Second, individual differences in cardiac interoceptive accuracy (CIAcc) [24] likely played a role. Participants with higher interoceptive accuracy may have detected the artificial manipulation more readily, preventing the relaxation associated with the illusion. Future designs for arousal reduction must therefore account for individual differences in baseline heart rate and interoceptive sensitivity.

CONCLUSION

This study proposed a pseudo-heartbeat biofeedback system designed to promote meditation and sleep by inducing a subjective decrease in heart rate. Our results demonstrated that a subjective heart rate decrease and a state of mindfulness occurred simultaneously, independent of the manipulation rate.

This suggests that the subjective perception of cardiac deceleration yields mindfulness benefits comparable to actual physiological slowing. Furthermore, we identified a trade-off: while synchronization with the actual heart rate enhances the sense of ownership, higher manipulation rates elicit a stronger sensation of deceleration even without the illusion of ownership. However, no significant changes in arousal were observed, likely due to individual variations in baseline heart rate and interoceptive accuracy.

Several limitations constrained these findings, including high environmental noise [28], unintended tactile stimulation from low-frequency vibrations, and uncontrolled prior knowledge regarding the manipulation [29]. Additionally, the lack of detailed demographic data prevented a full analysis of individual differences. Future work will address these issues by rigorously controlling environmental and participant variables and employing long-term experimental designs. By refining the integration of exteroceptive and interoceptive senses, we aim to establish an interactive meditation support system effective for alleviating sleep disorders.

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