Modulating Heart Activity and Task Performance using Haptic Heartbeat Feedback: A Study Across Four Body Placements

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Figure 1: Our haptic system simulating heart beats on four body locations – the chest, wrist, neck and ankle.

ABSTRACT

This paper explores the impact of vibrotactile haptic feedback on heart activity when the feedback is provided at four different body locations (chest, wrist, neck, and ankle) and with two feedback rates (50 bpm and 110 bpm). A user study found that the neck placement resulted in higher heart rates and lower heart rate variability, and higher frequencies correlated with increased heart rates and decreased heart rate variability. The chest was preferred in self-reported metrics, and neck placement was perceived as less satisfying, harmonious, and immersive. This research contributes to understanding the interplay between psychological experiences and physiological responses when using haptic biofeedback resembling real body signals.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; *Empirical studies in HCI*.

KEYWORDS

Haptic feedback, physiological computing, cardiac, interoception

1 INTRODUCTION

This paper explores where to place haptic feedback at different parts of the body to change people's heart activity. Interoceptive accuracy, the perception of internal bodily changes (e.g. changes in heartbeat), also called somatic markers, is closely tied to emotional experiences [6, 36]. When our body creates physiological reactions (e.g., changing heart rate) to external triggers, these responses become internal cues, setting off a feedback loop where our perception of somatic markers influences our emotional state. This is relevant for affective computing and types of computer interfaces where the system tries to help the user understand their physiological state.

Most interoceptive processes occur unconsciously, regulated by the autonomic nervous system responsible for involuntary bodily functions [9, 40]. The brain filters and prioritizes interoceptive

signals based on their relevance to immediate goals, allowing individuals to respond to somatic markers, such as increased heart rate, which may indicate stress or exertion [41], without the need for conscious intervention. These unconsciously interpreted somatic markers are formed through the association of physiological responses with past experiences or outcomes [14, 15]. Positive experiences lead to the creation of positive somatic markers, while negative experiences result in negative somatic markers. When faced with a decision, somatic markers generate immediate physiological responses based on past experiences associated with similar choices. These emotional signals serve as a guide for the generated emotion and subsequent information processing and decision-making.

Researchers have studied interoception through various methodologies to understand how individuals perceive and interpret somatic markers. Studies have explored how individuals interpret their heart activity, highlighting their implications on emotional experiences, memory recall, and decision-making. For example, Pollatos et al. [44] and Barrett et al. [3] found that individuals who are more aware of their heartbeat tend to report higher arousal to both pleasant and unpleasant stimuli, suggesting that a better perception of cardiac activity intensifies the perception of emotional experiences. Interoceptive sensitivity has been shown to positively impact objective anxiety levels during public speaking, measured by heart activity sensors [35, 54]. This suggests that individuals with increased sensitivity to somatic markers may exhibit better regulation of anxiety through enhanced heart rate variability.

In terms of impact on task performance, Werner et al. [55] discovered that improved cardiac perception correlated with better decision-making in tasks such as the Iowa Gambling Task, underscoring the influence of somatic markers on behavior. Similarly, Maia et al. [37] suggested that somatic markers could guide individuals toward advantageous decisions even before conscious awareness. However, Wölk et al. [57] found that while heightened cardiac perception aids decision-making in healthy individuals, it may hinder performance in panic disorder patients, for whom somatic cues are perceived as signals of threats.

The potential of somatic markers in shaping subjective emotional experiences, influencing emotional memory consolidation, and modulating heart activity should not be underestimated. Building upon this understanding, a new field of research has emerged focusing on the creation of artificial somatic markers, often called *"interoceptive illusions"*, including simulated heartbeats through visual, auditory, or haptics. Researchers have influenced participants to unconsciously link current experiences with bodily reactions that are not their own, altering their perception of the experience [7, 11–13, 27, 38, 39, 51]. These illusions have impacted participants' heart activity, demonstrating the bidirectional relationship between psychological experiences and physiological responses.

Despite previous work, there has been little research on haptics and interoceptive feedback, and in particular, how the placement of haptic devices on the body may impact the perception of heart activity and its consequent impact on cognition. For that reason, we created a vibrotactile haptic system simulating heartbeats on two frequencies (50 bpm and 110 bpm) and placed it a four different pulse points (the chest, wrist, neck, and ankle). Then, we explored the effect of these two variables on heart activity, task performance,

and subjective scores for haptic feedback. We also explored the role interoception accuracy has on these metrics.

This paper makes the following contributions: (1) it is the first work that explores the role of vibrotactile stimulation at different body locations on manipulating heart rate through interoceptive feedback, (2) it presents a user study evaluating vibrotactile location and frequency on heart rate, demonstrating how these factors contribute to the creation of interoceptive illusions, and (3) it presents design guidelines for haptic *interoceptive illusions* using heartbeats. By focusing on the manipulation of heart rate via interoceptive mechanisms, this work has significant implications for researchers creating systems designed to manipulate users' physiological states.

In the remainder of this paper, we first review related work and identify the research gap that we are addressing. Then, we describe the system we have developed for creating vibrotactile feedback and a user study with this system to explore the impact of feedback location and frequency. In section 4, we present the results from the user study in terms of impact on heart rate, task performance, and user feedback. Next, we discuss the results and provide some design guidelines. Finally, we present the limitations of the work and present directions for future work.

2 RELATED WORK

Researchers have investigated the manipulation of heart rate feedback through diverse modalities, including visual, auditory, and haptic stimuli, aiming to understand the impact of this artificial somatic marker on self-perception and physiological reactions.

2.1 Cardiac Feedback through Sound

In early-stage research [39] of artificial somatic markers, participants were instructed to walk towards the edge of a building while a square wave generator produced heartbeat sounds, with the experimenter increasing the false feedback rate based on the participant's location. Higher false heart rate feedback influenced self-report fear of heights and was assumed to induce self-focus in the subjects. This means that when participants received false feedback about their heart rates, they became more focused on themselves, particularly their internal physiology. Iodice et al. [28] also explored the effects of false heartbeat acoustic feedback on participants during cycling tasks at various intensities, revealing that faster feedback led to higher perceived effort.

2.2 Cardiac Feedback through Visuals

Research on visual systems for providing cardiac feedback has been a focal point in the field. Several studies [27, 51] have investigated desynchronized cardiac feedback within the framework of the rubber hand illusion in Augmented Reality (AR) environments. Aspell et al. [1] also explored cardio-visual desynchrony by using a real-time body image projection and flashing outlines suggesting user heartbeat. In these investigations, asynchronous feedback, characterized by a mismatch between the virtual heart feedback and the participant's actual heartbeat, led to a reduced sense of virtual body ownership compared to synchronous feedback. These findings indicate that discrepancies between the visual representation of heart rate and the participant's perceived internal physiological signals can weaken the illusion of self on virtual reflections.

On a public speech task, Makkar et al. [38] created a simulated electrocardiogram feedback, featuring either a false increase or decrease in heart rate. Participants who were led to believe that their heart rate was increasing prior to the speech reported higher levels of negative affect and more negative performance appraisals compared to those who believed their heart rate was decreasing.

2.3   Cardiac Feedback in VR

Exploring multi-modal feedback in Virtual Reality (VR), The VeRitas system [7] employed immersive VR cycling gameplay where the user's heart rate dictated the avatar's speed, integrating dynamic visual *interoceptive illusion* to enhance physical activity motivation. Findings suggested users could discern when heart rates were artificially lowered, creating a disconnection between task and user. El Ali et al. [22] provided visual feedback of a pulsating heart image and audio feedback of systole and diastole activity in VR. They found that audio-based representations can be more effective than visual alone in enhancing cardiac interoceptive awareness.

2.4   Cardiac Feedback through Haptics

Although visual and auditory artificial somatic markers have been shown to have significant effects on self-perception, Chen et al. [8] found a preference among participants for non-visual feedback. When considering various combinations of audio, visual, and haptic feedback, participants expressed a strong preference for audio-haptic feedback, while visual feedback was noted to be distracting. Choi et al. [11] demonstrated that tactile heart feedback was preferred by participants and can be more effective in both increasing and decreasing heart rate, while auditory stimulation was perceived as the most disturbing, and visual stimulation as the most stressful. Tactile stimulation also showed higher effectiveness in reducing stress levels as measured by heart rate variability.

Following the guidelines from Chen et al. [8], Dey et al. [16] delivered heart rate feedback through sounds and haptic feedback through hand-held controllers in a VR task. They found that faster heart rate feedback increased self-reported excitement, but excitement decreased beyond +15% higher than real heart rate, potentially due to participants' realization of feedback manipulation. Additionally, self-reported scariness, nervousness, and fear increased with faster heart rate feedback, consistent with associations between faster heart rates and negative emotions in audio-visual media. However, manipulating heart rate feedback did not significantly affect the participant's own physiological signals.

The EmotionCheck system [12] explored the impact of heart rate-based interventions on anxiety by employing wrist-worn haptic motor feedback, simulating a heartbeat of 60 beats per minut (bpm) (slow condition) or conveying real heart rate data. Participants exposed to slow heart rate feedback reported significantly reduced anxiety compared to both the control group and other conditions. This decrease was attributed to participants' belief that the vibrations corresponded to their real heart rate. Those receiving real heart rate feedback did not demonstrate significantly heightened anxiety levels, although some reported increased nervousness. Notably, participants who consciously used the vibrations to regulate their emotions experienced higher anxiety levels, suggesting that excessive focus on bodily cues may not be ideal during stressful

tasks. Later, Costa et al. introduced the BoostMeUp system [13], which used smartwatch haptic feedback linked to the user's heart rate, adjusted to be either 30% lower or 30% higher than the participant's baseline heart rate. Participants noted reduced anxiety with slow feedback and heightened anxiety with fast feedback. Task accuracy improved with slow feedback compared to fast feedback. However, participants took more time to answer questions with slow feedback and responded more quickly with fast feedback.

2.5   Effect of Body Placement on Haptic Feedback Perception

The impact of body location on haptic feedback has been explored across various studies, revealing diverse effects on user experience (UX), cognitive skills, and emotions. Basdogan et al. [4] demonstrated that force feedback on the hands enhances task performance and emotional engagement in virtual environments. Zeagler [59] explored functional, technical, and social considerations in on-body locations for wearable technology, noting that the placement affects usability, social acceptance, and overall UX. For instance, devices placed on the upper arm were generally more accepted and considered less intrusive than those placed on the wrist, which could interfere with everyday tasks. Zeagler also found that wearables on the torso provided better stability and were less prone to movement artifacts, making them more suitable for continuous monitoring applications. Additionally, the study highlighted that placing devices on the waist or hip allowed for easier access and interaction, enhancing usability in various contexts. Handelzalts et al. [26] found that providing tactile feedback close to the site of injury in telerehabilitation reduces cognitive load and increases emotional engagement. Raisamo et al. [45] highlighted that haptic feedback on hands or arms is more effective in conveying emotions like reassurance, whereas feedback on the back is less impactful. Jones et al. [30] showed that haptic feedback on the torso and limbs improves focus and emotional regulation for neurodiverse users, while facial feedback can be overwhelming. These studies collectively highlight the different ways in which the placement of haptic feedback can shape user experiences and emotional outcomes.

Even with recent advances in the effectiveness of physiological modulation and manipulated self-perception, *interoceptive illusion* systems have yet to thoroughly investigate how individuals interpret their heartbeat haptic sensations differently depending on where on the body they are perceived from. This is despite research indicating variations in haptic sensitivity across different body locations [17, 31, 33, 34]. This area of research represents a notable gap, as it can significantly impact the efficacy and suitability of interventions and technologies aimed at modulating physiological states through heartbeat perception. Addressing this gap is the current focus of our paper.

3   USER STUDY

In this section, we describe the research questions that motivate our research, then the system developed to explore these questions, and finally, the design of a user study with the system. The next section presents the results of the user study.

3.1 Research Questions

Previous studies have shown that awareness of heartbeat impacts emotional experience [3, 44], task performance [37, 55], and emotional regulation [35, 54, 58]. As discussed in the related work section, haptic feedback projects have aimed to enhance or distort heartbeat perception to modulate responses and task performance.

Studies on these haptic artificial somatic markers indicate that the frequency of haptic feedback on heartbeat vibrotactile design has a negative correlation with heart rate variability, where lower frequencies lead to lower levels of stress and higher frequencies lead to higher levels of stress. These projects have also found that the frequency of heartbeat activity was positively correlated with task accuracy and negatively correlated with answer time. We expect to see these results on the wrist placement, which has been used in previous projects [11–13], and plan to compare those results on heart activity and task performance with the other body placements (wrist, neck, and ankle).

Additionally, we aim to explore user perception of autotelics, immersion, awareness, distractedness, and preference of each haptic frequency in each placement to understand the possible effects on heart activity and task performance, as well as investigate the role of the user's interoception accuracy on the effects the feedback has on their heart activity and task performance.

This leads to the following research questions (RQs):

- RQ1: What is the impact of body location of vibrotactile feedback devices on the wearer's heart activity?
- RQ2: What is the impact of frequency of vibrotactile feedback devices on the wearer's heart activity?

3.2 Apparatus

To explore these research questions, we developed a system that could provide vibrotactile feedback, and measure user's heart activity in response. Based on the previous related research, we used vibrotactile modality instead of visual or auditory cues. This choice was also guided by the principles outlined in Wicken's Multiple Resource Theory[56], which suggests that different sensory modalities offer distinct cognitive processing channels. By using vibrotactile technology, and engaging the sense of touch, we are able to capitalize on an underutilized resource in interactive experiences like VR, while minimizing the risk of overloading other sensory channels. More importantly, the system was devised as an *interoceptive illusion* simulating a heartbeat, specifically created to replicate the sensation experienced at pulse points.

The haptic system architecture incorporated the Dayton Audio TT20-8 [1] audio transducer, which has a frequency response ranging from 20 Hz to 80 Hz. It measures approximately 9.5 cm in diameter and 3.4 cm in height, weighing 0.32 kg. The audio transducer was powered by the SMSL AD18 amplifier [2], with a frequency response spanning from 20 Hz to 20 kHz (±3 dB). A 40Hz sound profile of a single heartbeat (systole and diastole) was played at the rate required, either *50 bpm* or *110 bpm.*

Heart rate was measured using ECG data captured by a BITalino board[3]. This operated at 1000Hz, using three electrodes, following Einthoven's triangle lead-II placement. The ECG signals were wirelessly transferred via a Class II Bluetooth v2.0 module to a desktop computer running the OpenSignals software[4].

3.3 Methodology

Using the system described above, we conducted a within-subjects user study with two factors: haptic placement (4) × haptic frequency (2). Four pulse points were selected for the haptic placement because of their less-invasive potential and suitability for easy integration into wearable technology: chest (apical pulse), wrist (radial artery), neck (carotid artery), and ankle (posterior tibial artery). We employed a vibrotactile haptic system that simulates heartbeats, using two haptic frequencies - 50 bpm and 110 bpm. These frequencies correspond to ±10 of the minimum and maximum values within the typical resting heart rate range for adults, typically falling between 60 to 100 bpm [32]. The purpose was to generalize the perception of low and high levels of arousal.

Participants were asked to perform a cognitive task (N-back task [29]) through 12 trials: 2 training trials, 2 trials without any feedback (baseline), and 2 trials (50 bpm and 110 bpm) on each of the four locations (chest, wrist, neck, and ankle). A Latin square design was employed to ensure the balanced sequencing of placements across participants, while the selection of feedback rates was randomized within each placement. During the experiment, participants wore active noise-canceling headphones to mitigate the impact of the sound of the haptic actuator.

3.4 Metrics

This section outlines the methodologies used to analyze physiological and psychological responses during the user study, including electrocardiogram (ECG) processing, interoception accuracy (Schandry's heartbeat perception task), N-back cognitive task execution, and the evaluation of feedback. This was designed to investigate the interplay between haptic feedback placements and frequencies, cardiac activity, subjective experiences, and the embodiment of haptic feedback.

3.4.1 Heart Rate and Heart Rate Variability. During the trials, heart activity data was gathered using ECG, in order to analyze fluctuations in heart rate in response to the feedback variants and placements. We relied on the NeuroKit 2.0 Python packages[5] for all ECG processing. Despite instructing participants to avoid motion, the ECG signal was still affected by common noise. To address this issue, a pre-processing procedure was implemented involving the application of a third-order Butterworth band-pass filter[5] within the frequency range of 2 to 45Hz. This step aimed to reduce the impact of baseline drift caused by participants' respiration or bodily movements, as well as power-line interferences. For the detection of QRS complexes, the Pan-Tompkins [43] algorithm was employed, which squares the signal to highlight the QRS signal contribution and utilizes adaptive thresholds for each peak detection. We employed the Ultra-short-term protocol by Salahuddin et al.[46] and

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[1]Dayton Audio TT20-8: https://www.daytonaudio.com/product/1968/tt20-8-tactile-transducer-mini-bass-shaker-8-ohm
[2]SMSL AD18: https://www.smsl-audio.com/portal/product/detail/id/566.html

[3]BITalino (r)evolution: https://bitalino.com/products/plugged-kit-dual-mode-ble-bt
[4]Biosignals: https://www.pluxbiosignals.com/pages/opensignals
[5]NeuroKit 2.0: https://neuropsychology.github.io/NeuroKit/

a window of 60s for the analysis of time domain features of heart rate and heart rate variability, specifically Root Mean Square of the Successive Differences (RMSSD).

3.4.2   Task Performance. We selected the N-back task [29], to induce cognitive load, and as a distractor for the *introceptive illusion*, for the participants to not focus on the feedback. A 2-back task was used, consisting of a trial length of 20 letters of the English alphabet, each involving the presentation of stimuli for 500 milliseconds followed by an interval of 3000 milliseconds with an empty screen. Participants were instructed to click on a computer keyboard's space bar if the letter on the screen matched the one presented two steps back in the sequence. Within each trial, 30% of the letters were 2-back occurrences, randomly placed. We recorded metrics of answer time, which represented the interval between the showing of the 2-back letter and the pressing of the space bar, and task accuracy was calculated as follows:

$$\text{N-back accuracy} = \frac{TP + TN}{TP + TN + FP + FN} \qquad (1)$$

, with: TP = correct detection, TN = correct no-detection, FP = incorrect detection, FN = incorrect no-detection.

We implemented a short 2-back test duration to minimize haptic habituation and focus on studying the response to short-term stimuli rather than long-term ones. Prolonged exposure to haptic feedback can induce habituation, diminishing participants' sensitivity to the stimuli over time. Moreover, longer experiments would likely result in reduced engagement and attention, resulting in fluctuations in heart rate measurements that may not accurately reflect the true effects of haptic feedback.

3.4.3   Autotelics, Harmony, and Immersion. After each trial, participants answered questions on a 5-point Likert (1 being "strongly disagree" and 5 being "strongly agree") scale to provide feedback on 'Autotelics' (intrinsic enjoyment and satisfaction derived from the haptic experience itself, regardless of external goals or outcomes), 'Harmony' (coherence and congruence between the haptic feedback and the user's actions or intentions), and 'Immersion' (sensation of being engrossed and mentally engaged in the haptic experience). The questions were a subset of the Haptic Experience (HX) dimensions questionnaire by Sathiyamurthy et al.[47].

3.4.4   Feedback Embodiment. Following each trial, participants were prompted to assess whether they felt their actual heartbeat was slower, equal to, or faster than the rate of the haptic feedback they received. They were informed that if their heartbeat and the feedback rate were within a 14.5 bpm range of each other, the system would consider them equal. This assessment aimed to assess the level of embodiment of the interoceptive system, specifically examining how individuals perceive the feedback they receive as integrated with their own bodily experiences.

A metric of perceptual accuracy was established by comparing reported feedback embodiment perception with actual heart rate. If the real heart rate and the frequency of haptic feedback were within 14.5 bpm of each other, they were considered equal, aligning with findings from previous research on real-world heart rate intervals [2]. The correct perception was indicated if participants reported

the feedback as lower, congruent, or higher, and this matched the comparison.

3.4.5   Interoception Accuracy. Schandry's mental heartbeat tracking [48], also known as the heartbeat perception task, is a method used to assess an individual's interoceptive accuracy or ability to perceive internal bodily sensations accurately. In this task, participants mentally count their heartbeats without using external aids, such as taking their pulse, during short intervals of time. After each interval, they report the number of heartbeats they counted, which is then compared to the actual number of heartbeats recorded through physiological measures like electrocardiography. Interoception accuracy (IAcc) was calculated according to the formula:

$$IAcc\ score = \frac{1}{3} \sum_{i=1}^{3} (1 - \frac{|na_i - nr_i|}{na_i}) \qquad (2)$$

, with:

i = number of time intervals (25s, 35s, 45s),
na_i = number of heartbeats (measured by ECG),
nr_i = number of reported heartbeats.

3.4.6   Distractedness, Awareness, and Preference. After all trials were completed, participants were asked to rank each feedback placement by how distracting the feedback was at that location, how aware they were of the feedback during the trials, and their overall preference. These rankings were converted into scores from 1 (lowest) to 4 (highest) and analyzed.

3.5   Participants

We recruited 20 participants (11 identified as women and 9 as men), between 22 and 34 years of age (M = 29.5, *SD* = 3.52). Participants confirmed having no cardiac problems and that they had not ingested caffeine in the 5 hours before the experiment. Five hours is the average time it takes to metabolize half of a caffeine dose [19], which affects cardiovascular responses. Participation was voluntary, and no compensation was provided.

3.6   Procedure

Upon arrival, participants were informed they would be playing a cognitive game while feeling vibrations simulating a heartbeat on four locations (chest, wrist, ankle, and neck), one location at a time, while connected to ECG sensors. They were given an image of sensor placement (Einthoven's triangle lead-II) and were asked to place the three electrodes on their own body.

After confirming correct signal collection, participants were asked to report the number of heartbeats they counted, without the aid of taking their pulse or any other physical aid, through six counting trials of Schandry's heartbeat perception task, two trials of each duration (25s, 35s, 45s), with 30s of rest in between.

Then, they were asked to perform two training trials of the 2-back task, described in 3.4.2. These training trials were meant to mitigate the additional cognitive load associated with learning a new task. After the two training trials, the participants performed ten trials with the haptic actuator on the four different placements (chest, wrist. neck, and ankle), with one of the two haptic frequencies (50

bpm and 110 bpm) in each placement. Two additional trials without any feedback were added to be used as the participant's baseline. The sequence of the 12 trials (10 with feedback plus 2 without feedback) was counterbalanced with a Latin square design.

The interval between trials encompassed several steps: the researcher removed the device from the participant's body, participants completed experiment questionnaires, the researcher reattached the device to a new location on the body, and there was a 20-second preparation period before the start of feedback and the n-back task. During this 20-second period, participants were shown a blank screen to help them focus, adapt to the device, and ensure successful data transmission initiation.

After placing the haptic actuator in each placement, there was a phase of haptic calibration. We started by adjusting a velcro elastic band to the body placement, securing the audio transducer in place. In our calibration procedure, we gradually increased the signal's amplitude from 0 dB and instructed participants to indicate when they first perceived the vibration. This point marked their minimum sensitivity threshold for the specific placement. We then gradually raised the amplitude until participants reported discomfort. The final amplitude used for the trial was calculated midway between the initial perception and discomfort levels for that particular body location. This approach was designed to mitigate the variations in sensitivity across different body parts [24], aiming for uniform haptic feedback perception across all locations.

In trials with haptic feedback, participants were asked to fill out the haptic experience form (section 3.4.3) and a feedback embodiment question (section 3.4.4). At the end of all trials, participants were asked to rate the four placements regarding distractedness, awareness, and preference, as described in section 3.4.6.

4 RESULTS

Unless otherwise stated, our results were analyzed via Friedman tests followed by a post hoc analysis with Wilcoxon signed-rank tests (Bonferroni corrected). The key results found include:

- Haptic placement and frequency significantly affected participants' **heart rate** and **heart rate variability**.
- Haptic placement did not significantly impact participants' **task accuracy** or **answer time**.
- Haptic frequency significantly affected participants' **answer time**, with higher frequencies leading to lower answer times.
- Haptic placement and frequency significantly affected participants' self-reported levels of **autotelics** and **harmony**. Neck placement was less autotelic, while chest placement was more harmonious.
- Haptic placement significantly affected participants' ranking of **distraction**, **awareness**, and **preference**, with neck placement being the most distracting, resulting in higher awareness and less favored.
- **Interception accuracy** correlated with participants' **heart rate** and **heart rate variability**, indicating that higher accuracy was associated with lower levels of anxiety.

These are presented in more detail in the rest of this section.

4.1 Heart Activity

The mean results regarding heart rate can be seen in Figure 2 and for heart rate variability in Figure 3.

We found a significant effect of **haptic placement** in participants' *heart rate* ($\chi^2(4)$ = 15.422, p = .004). Post hoc analysis revealed a significantly higher *heart rate* during haptic feedback on the neck compared to the chest (Z = -3.373, p = .007) and baseline (i.e., no feedback) conditions (Z = -2.846, p = .044). No other significant differences were found (p > .084). We also found a significant effect of **haptic placement** in participants' ***heart rate variability*** ($\chi^2(4)$ = 36.578, p < .001). Post hoc analysis revealed significantly lower *heart rate variability* during haptic feedback on the neck compared to the baseline (Z = 4.743, p < .001), chest (Z = 5.481, p < .001), and wrist conditions (Z = -3.057, p = .022); and higher heart rate variability during haptic feedback on the chest when compared to the ankle condition (Z = -2.951, p = .032). No other significant differences were found (p > .114).

For **chest placement**, neither the 50 bpm nor the 110 bpm condition were able to significantly change *heart rates* from baseline (Z = = 1.543 and p = .368, Z = -2.058 and p = .119, respectively). However, the 110 bpm condition led to significantly higher *heart rates* than the 50 bpm (Z = 2.601, p = .001). In terms of *heart rate variability*, the 110 bpm condition led to significantly lower RMSSD than the baseline and the 50 bpm condition (Z = 3.167 and p = .005, Z = 3.167 and p < .001, respectively). The 50 bpm condition did not significantly alter the *heart rate* from baseline (Z = .686, p = 1.000).

For **wrist placement**, neither the 50 bpm nor the 110 bpm condition was able to significantly change *heart rates* from baseline (Z = 1.886, p = .178, Z = -.343 and p = 1.000, respectively). The two conditions also did not significantly differ from each other (Z = 2.229, p = .077). In terms of *heart rate variability*, the 50 bpm condition significantly increased the RMSSD from baseline (Z = -2.572 and p = .030), but the 110 bpm condition did not significantly alter the RMSSD from baseline (Z = .000 and p = 1.000).

For **neck placement**, neither the 50 bpm nor the 110 bpm condition were able to significantly change *heart rates* from baseline (Z = .000 and p = 1.000, Z = -2.250 and p = .073, respectively). The two conditions also did not significantly differ from each other (Z = 2.250, p = .073). In terms of *heart rate variability*, the 110 bpm condition significantly decreased the RMSSD from baseline and the 50 bpm condition (Z = 3.167 and p = .005, Z = -3.833 and p < .001, respectively). The RMSSD from the 50 bpm condition did not differ from the baseline (Z = -.667 and p = 1.000).

For **ankle placement**, the 110 bpm condition was able to significantly increase *heart rates* from baseline (Z = -3.333, p = .003) but did not differ from the 50 bpm condition (Z = 1.667, p = .287). The 50 bpm condition did not differ from the baseline either (Z = -1.667, p = .287). In terms of *heart rate variability*, the 110 bpm condition significantly decreased the RMSSD from baseline and from the 50 bpm condition (Z = -3.000 and p = .008, Z = 5.500 and p < .001, respectively). The 50 bpm condition also decreased the RMSSD from the baseline (Z = 2.500, p = .037).

We found a significant effect of ***haptic frequency*** in participants' *heart rate* ($\chi^2(4)$ = 16.444, p = < .001). Post hoc analysis revealed a significantly higher *heart rate* during 110 bpm when compared to the 50 bpm (Z = 3.333, p = .003) and *baseline* (i.e., no
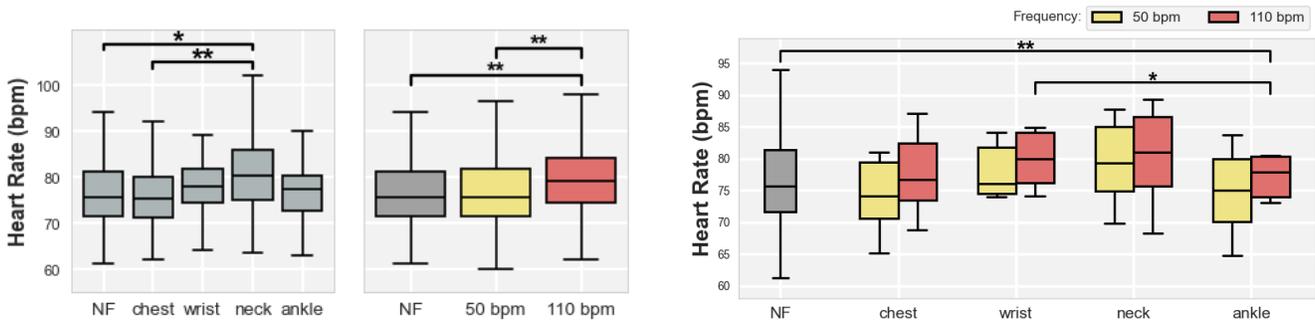
Figure 2: Mean heart rate across haptic placement and haptic frequencies ('NF' stands for 'no feedback'). * denotes p<.05, ** denotes p<.01, * denotes p<.001**

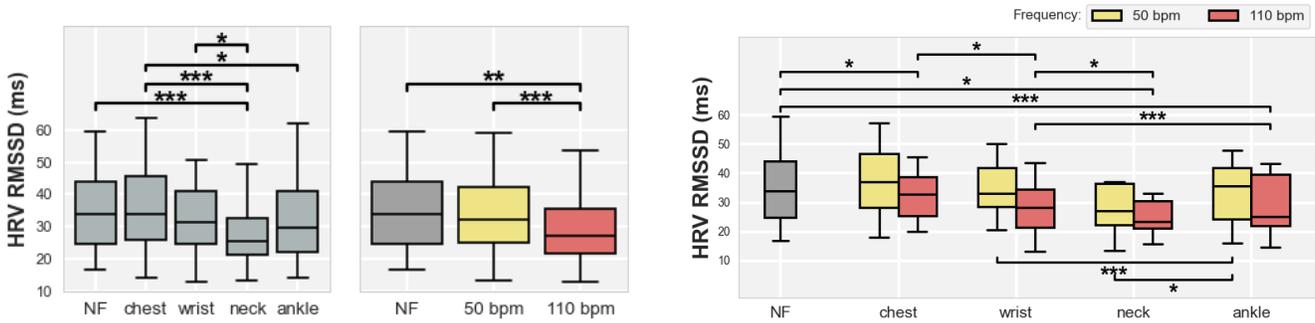**Figure 3: Mean heart rate variability across haptic placement and haptic frequencies ('NF' stands for 'no feedback'). * denotes p<.05, ** denotes p<.01, *** denotes p<.001**

feedback) conditions (Z = -3.667, p = .001). No significant differences were found between the 50 bpm and the baseline conditions (Z = -.333, p = 1.000).

As before, we also found a significant effect of ***haptic frequency*** in participants' *heart rate variability* ($\chi^2(4)$ = 20.111, p < .001). Post hoc analysis revealed a significantly lower *heart rate variability* during 110 bpm when compared to the 50 bpm (Z = -4.333, p < .001) and *baseline* conditions (Z = 3.167, p = .0050). No significant differences were found between the 50 bpm and the baseline conditions (Z = -1.167, p = .730).

For the **50 bpm condition**, there was no significant effect of *haptic placement* in participants' *heart rate* ($\chi^2(4)$ = 5.379, p < .251) but there was a significant effect of *haptic placement* in participants' RMSSD ($\chi^2(4)$ = 27.350, p < .001). The *ankle* condition led to significantly higher RMSSD than the wrist and the neck (Z = 5.143, p < .001 and Z = -3.242, p = .012, respectively). No other significant differences were found for the 50 bpm condition (p > .052).

For the **110 bpm condition**, we found a significant effect of *haptic placement* in participants' *heart rate* ($\chi^2(4)$ = 18.756, p < .001). The ankle condition led to significantly higher *heart rates* than baseline (Z = -3.584, p = .003) and the *wrist* condition (Z = 3.162, p = .016). In terms of heart rate variability, by analyzing just the 110 bpm condition, we found a significant effect of haptic placement in participants' *heart rate* ($\chi^2(4)$ = 45.022, p < .001). Both neck and ankle conditions led to significantly lower RMSSD than the baseline

condition (Z = -3.268, p = .011 and Z = 5.587, p < .001, respectively) and the wrist condition (Z = 3.162, p = .016 and Z = 5.481, p < .001, respectively), while the chest condition led to significantly higher RMSSD than the baseline (Z = 3.162, p = .016). No other significant differences were found for the 110 bpm condition (p > .061).

4.2 Task Performance

As described in section 3.4.2, different metrics of task performance were evaluated: answer time and task (N-back) accuracy. Mean results for answer times regarding **haptic placement × haptic frequency** can be seen in Figure 4. We did not find a significant effect of **haptic placement** in participants' *task accuracy* ($\chi^2(4)$ = 5.763, p = .218) or *answer time* ($\chi^2(4)$ = 7.160, p = .128).

For **chest placement**, there was no significant effect of *haptic frequency* in participants' *task accuracy* ($\chi^2(2)$ = .984, p = .611) but there was an effect in *answer time* ($\chi^2(2)$ = 15.474, p < .001). The 110 bpm condition led to reduced *answer time* than the baseline and the 50 bpm condition (Z = 3.407 and p = .002, Z = -3.407 and p = .002, respectively). No significant differences were found between the 50 bpm condition and the baseline (Z = .000, p = 1.000).

For **wrist placement**, there were no significant effect of *haptic frequency* in participants' *task accuracy* ($\chi^2(2)$ = 2.348, p = .309) or answer time ($\chi^2(2)$ = 1.368, p = .504).

For **neck placement**, there was significant effect of *haptic frequency* in participants' *task accuracy* ($\chi^2(2)$ = 7.147, p = .028). No
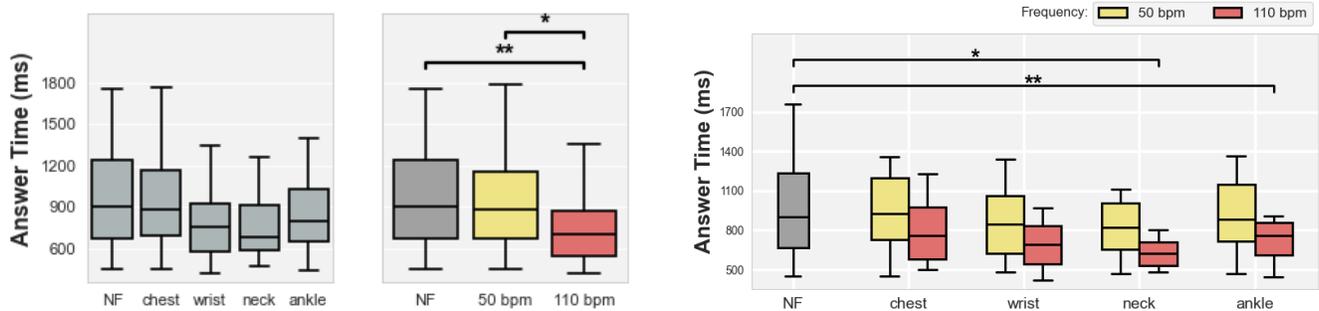
**Figure 4: Mean answer time in milliseconds across haptic placement and haptic frequencies ('NF' stands for 'no feedback'). *
denotes p<.05, ** denotes p<.01, *** denotes p<.001**

significant differences on *task accuracy* were found on a pairwise comparison ($p > .098$). There was also found a significant effect of *haptic frequency* in participants' *answer time* ($\chi^2(2) = 7.600$, $p = .022$). The 110 bpm condition led to reduced answer times from the baseline ($Z = 2.530$, $p = .034$) but did not significantly differ from the 50 bpm condition ($Z = -2.214$, $p = .081$).

For **ankle placement**, there was no significant effect of *haptic frequency* in participants' *task accuracy* ($\chi^2(2) = .521$, $p = .771$) but there was an effect in *answer time* ($\chi^2(2) = 12.700$, $p = .002$). The 110 bpm condition led to reduced answer times from the baseline and 50 bpm condition ($Z = 3.162$ and $p = .005$, $Z = -3.004$ and $p = .008$, respectively). The 50 bpm condition did not differ from the baseline ($Z = .158$, $p = 1.000$).

We also did not find any significant effect of **haptic frequency** in participants' *task accuracy* ($\chi^2(2) = 3.179$, $p = .204$). However, there were significant differences in *answer time* ($\chi^2(2) = 10.900$, $p = .004$). Post hoc analysis revealed that participants were quicker to press the key to indicate a n-back occurrence during the 110 bpm condition than during the baseline ($Z = 3.004$, $p = .008$) or the 50 bpm condition ($Z = -2.688$, $p = .022$).

For the **50 bpm condition**, there was no significant effect of *haptic placement* in participants' *task accuracy* ($\chi^2(4) = 4.454$, $p = .348$) or *answer time* ($\chi^2(4) = 2.711$, $p = .607$).

For the **110 bpm condition**, there was no significant effect of *haptic placement* in participants' *task accuracy* ($\chi^2(4) = 2.195$, $p = .700$), but there were significant differences in *answer time* ($\chi^2(4) = 16.680$, $p = .002$). Post hoc analysis revealed that, during the 110 bpm condition, answer times were reduced from the baseline with the neck and ankle placements ($Z = -2.900$ and $p = .037$, $Z = -3.600$ and $p = .003$, respectively).

4.3 Autotelics, Harmony, and Immersion

The mean results for *autotelics*, *harmony* and *immersion* regarding **haptic placement** can be seen in Figure 5 and Figure 6.

Regarding *autotelics*, we found a significant effect of **haptic placement** ($\chi^2(3) = 27.152$, $p < .001$). Post hoc analysis revealed that the neck placement was scored as significantly less satisfying than the chest ($Z = 4.838$, $p < .001$), the wrist ($Z = -2.694$, $p = .042$), and the ankle ($Z = 3.980$, $p < .001$). No other significant differences between placements were found ($p > .193$).

The 50 bpm condition was ranked higher than the 110 bpm condition on *autotelics* for the **chest placement** ($Z = 3.447$, $p < .001$), the **wrist placement** ($Z = 2.606$, $p = .009$), the **neck placement** ($Z = 3.314$, $p < .001$), and the **ankle placement** ($Z = 2.955$, $p = .003$).

Analyzing the effect of the ***haptic frequencies***, we found that the 50 bpm condition scored significantly higher on *autotelics* than the 110 bpm condition ($Z = 3.899$, $p < .001$).

For the **50 bpm condition**, there was significant effect of *haptic placement* in participants' *autotelics* ($\chi^2(3) = 23.198$, $p < .001$). The ankle was ranked significantly higher for *autotelics* than the wrist ($Z = 4.002$, $p < .001$) and the neck ($Z = -2.969$, $p = .018$). The chest scored significantly higher for *autotelics* than the ankle ($Z = 4.131$, $p < .001$). For the **110 bpm condition**, there was significant effect of *haptic placement* in participants' *autotelics* ($\chi^2(3) = 21.603$, $p < .001$). The ankle placement was again ranked significantly higher for *autotelics* than the wrist ($Z = 4.002$, $p < .001$) and the neck ($Z = -2.969$, $p = .018$), and lower than the chest ($Z = 4.131$, $p < .001$).

Regarding *harmony*, we found a significant effect of haptic placement ($\chi^2(3) = 27.152$, p , $.001$). The chest placement was ranked as more harmonious with the task than the neck ($Z = 4.838$, p < .001), the wrist ($Z = 4.470$, p < .001), and the ankle ($Z = -3.429$, $p = .004$). No other significant differences were found ($p > .954$).

The score for *harmony* between the 50 and 110 bpm conditions did not differ for the **chest** ($Z = .690$, $p = .490$), the **wrist** ($Z = 1.816$, $p = .069$), nor the **ankle** ($Z = 1.076$, $p = .282$). However, participants ranked the 50 bpm condition significantly higher than the 110 bpm condition with the neck placement ($Z = 2.943$, $p = .003$).

Analyzing the effect of the ***haptic frequencies***, we found that the 50 bpm condition scored significantly higher on *harmony* than the 110 bpm condition ($Z = 2.129$, $p = .033$). For the **50 bpm condition**, there was significant effect of *haptic placement* in *harmony* ($\chi^2(3) = 12.665$, $p = .005$). The wrist placement was ranked lower on *harmony* than the chest ($Z = -3.292$, $p = .001$), the neck ($Z = 3.808$, $p = .006$), and the ankle ($Z = 4.777$, $p < .001$). For the **110 bpm condition**, there was significant effect of *haptic placement* in *harmony* ($\chi^2(3) = 27.656$, $p < .001$). The wrist was again ranked lower on harmony than the chest ($Z = -3.062$, $p = .013$), the neck ($Z = 4.470$, $p < .001$), and the ankle ($Z = 4.225$, $p < .001$).

Regarding *immersion*, we found a significant effect for **haptic placement** ($\chi^2(3) = 11.303$, $p = .010$); no significant differences were observed between specific pairs of placements ($p > .061$).
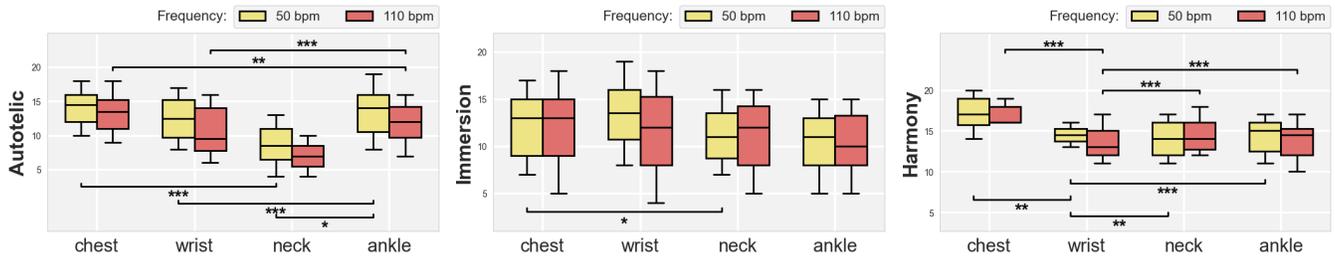
Figure 5: Scores the autotelic, immersion and harmony dimensions across haptic placement and haptic frequencies. * denotes p<.05, ** denotes p<.01, *** denotes p<.001

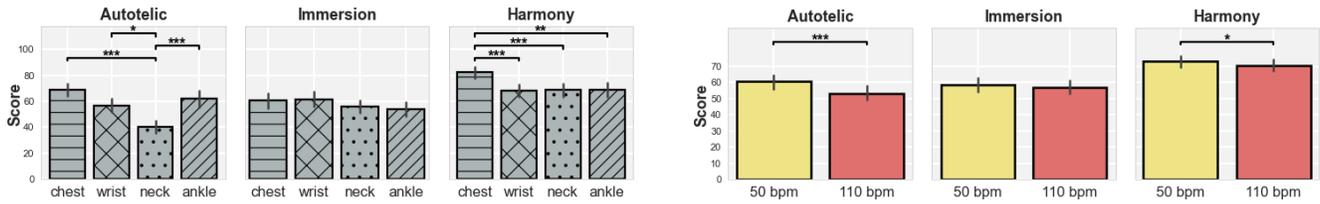Figure 6: Scores for autotelic, immersion and harmony across haptic placement (left) and haptic frequencies (right). * denotes p<.05, ** denotes p<.01, *** denotes p<.001

The score for *immersion* between the 50 bpm condition and the 110 bpm condition did not differ for the **chest** (Z = -.143, *p* = .887), the **wrist** (Z = .612, *p* = .541), nor the **ankle** (Z = -.884, *p* = .377). However, participants ranked the 50 bpm condition significantly higher than the 110 bpm condition on immersion with the **neck placement** (Z = 2.943, *p* = .003).

Analyzing the effect of the ***haptic frequencies***, we found that the 50 bpm condition and 110 bpm condition did not differ in *immersion* (Z = 1.330, *p* = .183). For the **50 bpm condition**, there was significant effect of *haptic placement* in *immersion* ($\chi^2(3)$ = 12.665, *p* = .005). The chest placement was ranked significantly more immersive than the neck placement (Z = -2.905, *p* = .022). For the **110 bpm condition**, there was no significant effect of *haptic placement* in *immersion* ($\chi^2(3)$ = 5.965, *p* = .113).

4.4 Effects on Feedback Embodiment

As explained in section 3.4.4, participants were asked to indicate whether they perceived their actual heartbeat as slower (converted to "-1"), equal to (converted to "0"), or faster (converted to "1") than the rate of the haptic feedback they received. We refer to the perception of equal rates between real heart activity and feedback as *perception congruence*. The number of trials corresponding to perceptions of lower, congruence, and higher, can be seen in Figure 7. We found no significant effect of ***haptic placement*** in participants' *perception congruence* ($\chi^2(3)$ = 6.643, *p* = .084).

The 50 bpm condition was reported more congruent with real heart perception than the 110 bpm condition for the **chest** (Z = 8.100, *p* = .002), **neck** (Z = 4.000, *p* = .039), and **ankle** placement (Z = 8.100, *p* = .002). For the **wrist** placement, the two conditions did not differ in perception congruence (Z = .364, *p* = .549).

We found a significant effect of ***haptic frequency*** in participants' *perception congruence* (Z = 3.330, *p* < .001), where the 50 bpm
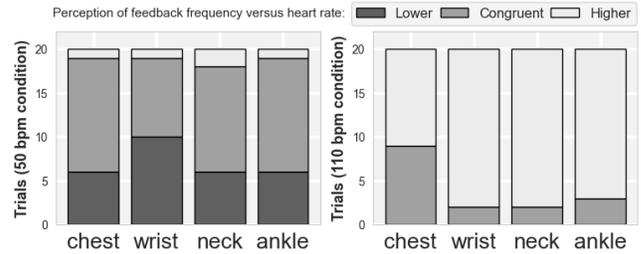

Figure 7: Trials the participants reported lower, congruent, or higher perception between the haptic feedback frequency and their own heart rate across haptic placements.

condition was reported more congruent with real heart perception than the 110 bpm condition.

For the **50 bpm**, there was no significant effect of *haptic placement* on *perception congruence* ($\chi^2(3)$ = 3.732, *p* = .292). For the **110 bpm**, there was a significant effect of *haptic placement* on *perception congruence* ($\chi^2(3)$ = 11.333, *p* = .010). The wrist was reported to be significantly less congruent than the ankle and the neck (Z = -2.646 and *p* = .008, Z = -2.646 and *p* = .008, respectively).

4.5 Effects of Interoception Accuracy

The participant's interoception accuracy was measured as described on 3.4.5. The Pearson product-moment correlation was run to determine the relationship between the participant's interoception accuracy and the participant's average heart activity, task performance, trial perception accuracy (described in section 3.4.4), and haptic experience dimensions.
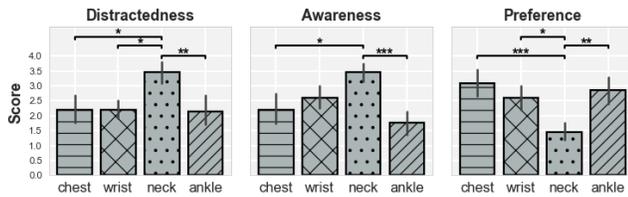
Figure 8: Ranking score for distractedness, awareness, and preference across haptic placement. * denotes p<.05, ** denotes p<.01, *** denotes p<.001

There was no correlation between participant's **interoception accuracy** and **n-back accuracy** (r = -.135, p = .570), **answer time** (r = -.070, p = .767), or **trial perception accuracy** (r = .326, p = 0.186). However, there was a strong, negative correlation between **interoception accuracy** and **heart rate** (r = -.847, p < .001), and a strong, positive correlation between **interoception accuracy** and **heart rate variability** (r = .472, p = .048).

Interception accuracy showed no significant correlation with **autotelic** reports (r = -.124, p = .601). However, it displayed a negative correlation with **immersion** (r = -.498, p = .025) and **harmony** (r = -.501, p = .024).

4.6 Participant Rankings

The mean results for ranking scores for distractedness, awareness, and preference can be seen in Figure 8. There was a significant effect of **haptic placement** in participants' *distractedness* ($\chi^2(3)$ = 5.763, p = .218), *awareness* ($\chi^2(3)$ = 5.763, p < .001) and *preference* ($\chi^2(3)$ = 19.140, p < .001).

For **distractedness**, the neck was ranked significantly more distracting than the chest (Z = 3.062, p = .013), wrist (Z = 3.062, p = .013), and ankle (Z = 3.184, p = .009). No other significant differences were found (p > 1.000).

For **awareness**, participants reported being significantly more aware of the feedback when it was placed on the neck than on the chest (Z = 3.062, p = .013) or the ankle (Z = 4.164, p < .001). No differences were found between chest, wrist, and ankle (p > .224).

For **preference**, participants ranked the neck less preferable than the chest (Z = -4.042, p < .001), the wrist (Z = -2.817, p = .029), and the ankle (Z = -3.429, p = .004). No significant differences were found between chest, wrist, and ankle (p > 1.000).

5 DISCUSSION

In this section, we connect our findings within the broader context of existing literature, its implications on interface design using artificial somatic markers and highlight avenues for future research.

5.1 Heart Rate and Heart Rate Variability

Firstly, and in answer to RQ2, our results show that **high frequencies were able to increase heart rate**. This is in contrast to previous projects with similar systems, which failed to achieve this result [8, 16]. We believe this difference could be attributed to haptic placement. since we found that the wrist placement, which has been the overwhelming choice for heartbeat haptic feedback in

previous research, had the least potential for heart activity modulation. In contrast, we found that higher heart rates could be achieved with ankle placement and high-frequency vibrations.

Thus, our research also answered RQ1, about the impact of body location. Ankle placement resulted in significantly higher heart rates with high-frequency vibration, and neck placement resulted in overall higher heart rates than the baseline condition. This indicates that if the goal is to elevate heart rate levels, irrespective of the feedback frequency, the neck placement is worth considering. However, for a dynamic biofeedback system aiming to regulate heart rates by both increasing and decreasing them, the neck placement should be avoided since its level of reported distractedness and awareness indicate higher levels of user discomfort.

In terms of RQ2, high-frequency feedback, particularly when applied to the neck, **reduced heart rate variability** and increased anxiety. It also proved notably effective when placed on the ankle. This discovery is significant as the ankle was rated as the least noticeable placement by participants, suggesting greater potential for subconscious effects. Furthermore, the minimal distraction reported with the ankle placement dismisses the hypothesis that heightened anxiety levels were solely due to participants focusing on the feedback rather than the task, thereby negating the importance of the physiological load of parallel cognitive processes.

Contrary to findings by Costa et al. [13], low-frequency feedback did not succeed in reducing anxiety in our study. This discrepancy in results may be due to different tasks used. There was a higher sustained cognitive load inherent in our N-back task, highlighted by Scharinger et al. [49], which contrasts with the mathematical task employed in Costa et al.'s study. This higher cognitive demand might have made the modulation of anxiety more difficult.

Finally, previous studies on heart rate variability modulation through heartbeat haptic stimulation, particularly focused on wrist-worn devices [11, 12]. They have suggested the potential of low haptic frequencies for increasing heart rate variability, such as the 60 bpm as employed by Costa et al. [12]. However, in our study, wrist placement showed no significant difference compared to the baseline condition, regardless of haptic frequency. The ineffectiveness of wrist placement in altering anxiety levels may be attributed to participants' familiarity with this feedback location, which some reported as feeling less engaging and could explain the preference scores for wrist placement. Conversely, chest placement consistently led to reduced anxiety, even with high feedback. Supported by high autotelic and harmony scores, participants found the chest location more enjoyable and coherent with their experience. Tactile systems located on the chest have demonstrated efficacy in anxiety reduction, possibly due to sensory receptor activation associated with comfort and safety sensations. However, whether vibrotactile feedback can produce comparable outcomes remains uncertain. While further research is necessary, our preliminary findings offer promising prospects in this area.

5.2 Heartbeat Haptics and Answer Time

In our study, the haptic feedback **did not affect task accuracy** in any combination of haptic placement and frequency. According to Attentional Control Theory, anxiety disrupts cognitive performance by interfering with attentional control [23]. Therefore, reducing

anxiety during a stressful task should theoretically improve cognitive performance, while increasing anxiety should lead to performance decrements. The BoostMeUp study [13], which successfully reduced participants' anxiety with low haptic frequency, proposed that this reduction contributed to the observed increase in accuracy. Thus, one might expect that inducing higher levels of anxiety, as observed in our study with high-frequency conditions, would lead to decreased task accuracy. However, our results did not show this, which suggests that there may be other factors at play that influence the relationship between anxiety and task performance, in particular, cognitive load. It is possible that the specific nature of the N-back task, individual differences in participants' coping mechanisms, or other contextual factors may have moderated the impact of anxiety on task accuracy. Further research is needed to fully understand these complexities and their implications for cognitive performance under varying levels of anxiety.

However, our findings on answer time concur with the findings in BoostMeUp [13]. Higher feedback frequencies led to significantly **lower answer times**. This phenomenon might be related to the findings of Droit-Volet and Meck [18], which highlighted the role of bodily rhythms in shaping temporal processing, suggesting a close connection between interoceptive signals and the perception of time intervals. Specifically, fluctuations in heartbeat have been shown to modulate individuals' sensitivity to the perception of time duration. Increased haptic frequencies could potentially have sped up how users perceive task duration, heightening the urgency felt with N-back occurrence. Exploring the link between temporal perception and haptic frequency is a key area of future research.

5.3 The Role of Interoception Accuracy

Contrary to our expectations, interoception accuracy positively impacted heart rate variability, decreased anxiety levels, and negatively impacted heart rate. We expected that individuals with higher interoception accuracy would perceive the haptic feedback differently from their actual heart rate, potentially leading to discomfort due to differences between the two signals. This could explain why individuals with higher interoception accuracy tended to rate the feedback lower in terms of harmony and immersion. Surprisingly, participants with higher interoception accuracy did not demonstrate superior perceptual accuracy, suggesting they were not better at distinguishing whether the heart rate was lower, congruent, or higher. This suggests that the haptic feedback may have impaired their ability to accurately interpret their bodily signals. It underscores the necessity of considering the implications for individuals when designing artificial somatic markers, particularly regarding the potential deprivation of this interoceptive mechanism when creating a real biofeedback haptic system. It also presents a new potential in applications where this deprivation is warranted and where they might benefit from replacing real somatic markers with artificial somatic markers, such as interventions for panic attacks.

The relationship between interoception accuracy, lower heart rate, and higher heart rate variability has been observed in prior studies [35, 54, 58], which hypothesized that higher interoceptive accuracy can lead to better self-awareness on moments where self-regulation is needed, indicating a better trained adaptive capacity to deal with stressors. When designing artificial somatic markers

meant to modulate heart activity, interoception accuracy should be taken into consideration as an indicator of the user's capacity to resist external regulation.

5.4 Limitations and Future Works

Despite the significant insights gained from the presented user study, it is important to acknowledge the constraints that may have influenced our findings. Firstly, we selected the particular audio transducer of our system to match those used in consumer haptic vests, aiming for comparable functionality and performance. However, the disproportionate size of the audio transducer seems to have led to a more intrusive experience for users, as inferred from the reported level of distractedness and awareness. This may have impaired the goal of providing feedback that operates on a subconscious level. As such, a future focus will be to find a more suitable smaller transducer or pivot to other types of vibrotactile actuators, allowing for more subtle haptic placement.

Another limitation of our study was the narrow range of ages among the participants, with all individuals falling between 22 and 34 years old. Age is a significant factor influencing haptic perception, with research indicating that older individuals may have reduced tactile sensitivity compared to younger individuals [20, 50]. Future studies should aim to recruit participants across a wider age spectrum to mitigate this limitation.

Using fixed haptic frequencies of 50 bpm and 110 bpm also presents a limitation. This approach aimed to streamline the interpretation of the haptic feedback and its average heart rate ranges. We acknowledge that this simplified approach may not fully capture the variations in individual perception and understanding of their own heart rate, limiting the potential of our system as a *interoceptive illusion* where participants unconsciously embody the feedback as their own bodily signals. Further studies should explore dynamic haptic feedback frequencies tailored to each participant's unique physiological responses and subjective perception.

The possible discomfort caused by the velcro strap required to secure the device represents another limitation. When attaching the device to the user, the researchers ensured comfort by asking if the participant needed the strap adjusted for a looser or tighter fit. However, it is recognized that wearing a strap may act as an additional stressor [21, 25]. Therefore, future studies should incorporate the velcro strap in baseline trials, even in the absence of any feedback stimuli.

Another limitation was that the duration of testing was only 1 minute, so these results primarily reflect the immediate physiological response to external stimuli rather than providing clues about what might happen in a longer-term physiological experience. Continuous haptic feedback may diminish its impact on heart rate after initial exposure due to the activation of the parasympathetic nervous system in response to elevated heart rate detection by baroreceptors [42]. However, discontinuous heartbeat stimuli could be a viable design choice for contexts that could benefit from heart rate spikes, such as gaming or emergency response.

Finally, when exclusively opting for the N-back task in a study, it is imperative to acknowledge the necessity of comprehending the impacts of somatic markers on various cognitive functions beyond working memory assessments. The applicability of these haptic feedback systems to, for example, sustained attention levels [10]

should be explored. Thus, there is a need to explore the impact of haptic feedback in a wider range of tasks.

Future research should also explore how simulated heartbeat feedback may influence social interactions, including its potential to create emotional contagion experiences and its role in emotional regulation strategies. Emotional contagion refers to the phenomenon where individuals unconsciously mimic the emotions of those around them, leading to shared emotional experiences. By incorporating shared simulated heartbeat feedback into social contexts, researchers can explore how it affects the transmission and synchronization of emotions between individuals. This could involve studying whether individuals exposed to other's heartbeat information are more likely to experience heightened empathy and interpersonal emotional understanding, which has been shown to enhance performance in collaboration [52, 53].

6 DESIGN GUIDELINES

In this section, we summarize our key findings in design guidelines for heart activity modulation, task performance, and perceptual factors. These recommendations aim to guide haptic placement and frequency in designing artificial somatic markers for heartbeats in various applications.

Considerations on haptic placement:

- For applications aiming to create spikes in **heart rate**, select high haptic frequency and, specifically, select the ankle placement with high feedback frequency.
- For applications aiming for **lower anxiety**, select the chest placement, as it results in higher heart rate variability compared to other placements, barring the ankle.
- For applications aiming to **increase anxiety**, select high haptic frequency and, specifically, select the neck placement with high frequency, as it results in lower heart rate variability compared to other placements.
- For applications aiming to give **subconscious feedback**, avoid using neck placement, as it results in higher reported levels of distractedness, and consider the ankle placement, as it results in lower reported levels of awareness.

Considerations on haptic frequency:

- To **reduce answer time**, select high haptic feedback frequency.
- To **increase** self-reported dimensions of **autotelic and harmony**, select low haptic feedback frequency.
- To **increase perceived congruence** between haptic feedback frequency and real heartbeat activity, select low haptic feedback frequency.

Additional considerations:

- When designing artificial somatic markers, consider the user's ability to distinguish feedback from their own bodily signals.
- Users with lower **interoception accuracy** experience overall higher levels of anxiety from the haptic feedback.

7 CONCLUSIONS AND FUTURE WORK

In our study, we explored how an artificial somatic marker representing haptic heartbeats, across four placements (RQ1) and two frequencies (RQ2), influences heart activity and task performance. We conducted a user study with a cognitive task to investigate these research questions on vibrotactile feedback location (RQ1) and vibration frequency (RQ2) effects on user heart rate and other factors. Our findings led to guidelines to increase heart rate, reduce heart rate variability, and decrease response time, contextualizing them within existing literature on physiology and psychology to advance understanding in this field.

In the future, our research will focus on investigating how simulated heartbeat feedback influences social interactions, including its potential to induce emotional contagion experiences and aid in emotional regulation strategies. By incorporating shared heartbeat feedback into social contexts, researchers can explore its effects on emotion transmission and synchronization between individuals. This research could examine whether exposure to others' heartbeat information enhances empathy and interpersonal emotional understanding, potentially improving collaboration performance.

ACKNOWLEDGMENTS

REFERENCES

[1] Jane Elizabeth Aspell, Lukas Heydrich, Guillaume Marillier, Tom Lavanchy, Bruno Herbelin, and Olaf Blanke. 2013. Turning body and self inside out: visualized heartbeats alter bodily self-consciousness and tactile perception. *Psychological science* 24, 12 (2013), 2445–2453.

[2] Robert Avram, Geoffrey H Tison, Kirstin Aschbacher, Peter Kuhar, Eric Vittinghoff, Michael Butzner, Ryan Runge, Nancy Wu, Mark J Pletcher, Gregory M Marcus, et al. 2019. Real-world heart rate norms in the Health eHeart study. *NPJ digital medicine* 2, 1 (2019), 58.

[3] Lisa Feldman Barrett, Karen S Quigley, Eliza Bliss-Moreau, and Keith R Aronson. 2004. Interoceptive sensitivity and self-reports of emotional experience. *Journal of personality and social psychology* 87, 5 (2004), 684.

[4] Cagatay Basdogan, Chih-Hao Ho, Mandayam A Srinivasan, and Mel Slater. 2000. An experimental study on the role of touch in shared virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)* 7, 4 (2000), 443–460.

[5] Stephen Butterworth et al. 1930. On the theory of filter amplifiers. *Wireless Engineer* 7, 6 (1930), 536–541.

[6] Giuseppe Calì, Ettore Ambrosini, Laura Picconi, Wolf Mehling, and Giorgia Committeri. 2015. Investigating the relationship between interoceptive accuracy, interoceptive awareness, and emotional susceptibility. *Frontiers in psychology* 6 (2015), 150835.

[7] Joey Campbell and Mike Fraser. 2019. Switching it up: Designing adaptive interfaces for virtual reality exergames. In *Proceedings of the 31st European Conference on Cognitive Ergonomics*. 177–184.

[8] Hao Chen, Arindam Dey, Mark Billinghurst, and Robert W Lindeman. 2017. Exploring the design space for multi-sensory heart rate feedback in immersive virtual reality. In *Proceedings of the 29th Australian conference on computer-human interaction*. 108–116.

[9] Wen G Chen, Dana Schloesser, Angela M Arensdorf, Janine M Simmons, Changhai Cui, Rita Valentino, James W Gnadt, Lisbeth Nielsen, Coryse St Hillaire-Clarke, Victoria Spruance, et al. 2021. The emerging science of interoception: sensing, integrating, interpreting, and regulating signals within the self. *Trends in neurosciences* 44, 1 (2021), 3–16.

[10] Alberto Chiesa and Alessandro Serretti. 2010. A systematic review of neurobiological and clinical features of mindfulness meditations. *Psychological medicine* 40, 8 (2010), 1239–1252.

[11] Kyung Yun Choi and Hiroshi Ishii. 2020. ambienBeat: Wrist-worn mobile tactile biofeedback for heart rate rhythmic regulation. In *Proceedings of the fourteenth international conference on tangible, embedded, and embodied interaction*. 17–30.

[12] Jean Costa, Alexander T Adams, Malte F Jung, François Guimbretière, and Tanzeem Choudhury. 2016. EmotionCheck: leveraging bodily signals and false feedback to regulate our emotions. In *Proceedings of the 2016 ACM international*

joint conference on pervasive and ubiquitous computing. 758–769.

[13] Jean Costa, François Guimbretière, Malte F Jung, and Tanzeem Choudhury. 2019. Boostmeup: Improving cognitive performance in the moment by unobtrusively regulating emotions with a smartwatch. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 3, 2 (2019), 1–23.

[14] Antonio R Damasio. 1996. The somatic marker hypothesis and the possible functions of the prefrontal cortex. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 351, 1346 (1996), 1413–1420.

[15] Antonio R Damasio, Daniel Tranel, and Hanna C Damasio. 1991. Somatic markers and the guidance of behavior: theory and preliminary testing. (1991).

[16] Arindam Dey, Hao Chen, Mark Billinghurst, and Robert W Lindeman. 2018. Effects of manipulating physiological feedback in immersive virtual environments. In Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play. 101–111.

[17] Nem Khan Dim and Xiangshi Ren. 2017. Investigation of suitable body parts for wearable vibration feedback in walking navigation. International Journal of Human-Computer Studies 97 (2017), 34–44.

[18] Sylvie Droit-Volet, Sophie Brunot, and Paula Niedenthal. 2004. BRIEF REPORT Perception of the duration of emotional events. Cognition and emotion 18, 6 (2004), 849–858.

[19] Ian C Dunican, Charles C Higgins, Maddison J Jones, Michael W Clarke, Kevin Murray, Brian Dawson, John A Caldwell, Shona L Halson, and Peter R Eastwood. 2018. Caffeine use in a super rugby game and its relationship to post-game sleep. European journal of sport science 18, 4 (2018), 513–523.

[20] Winnie Dunn, James W Griffith, Dory Sabata, Mary T Morrison, Joy C MacDermid, Amy Darragh, Roseann Schaaf, Brian Dudgeon, Lisa Tabor Connor, Leeanne Carey, et al. 2015. Measuring change in somatosensation across the lifespan. The American Journal of Occupational Therapy 69, 3 (2015), 6903290020p1–6903290020p9.

[21] Julia C Duvall, Lucy E Dunne, Nicholas Schleif, and Brad Holschuh. 2016. Active" hugging" vest for deep touch pressure therapy. In Proceedings of the 2016 ACM international joint conference on pervasive and ubiquitous computing: adjunct. 458–463.

[22] Abdallah El Ali, Rayna Ney, Zeph MC van Barlow, and Pablo Cesar. 2023. Is that my heartbeat? Measuring and understanding modality-dependent cardiac interoception in virtual reality. IEEE Transactions on Visualization and Computer Graphics (2023).

[23] Michael W Eysenck, Nazanin Derakshan, Rita Santos, and Manuel G Calvo. 2007. Anxiety and cognitive performance: attentional control theory. Emotion 7, 2 (2007), 336.

[24] Nazim Gizem Forta, Michael J Griffin, and Miyuki Morioka. 2012. Vibrotactile difference thresholds: Effects of vibration frequency, vibration magnitude, contact area, and body location. Somatosensory & Motor Research 29, 1 (2012), 28–37.

[25] Temple Grandin. 1992. Calming effects of deep touch pressure in patients with autistic disorder, college students, and animals. Journal of child and adolescent psychopharmacology 2, 1 (1992), 63–72.

[26] Shirley Handelzalts, Giulia Ballardini, Chen Avraham, Mattia Pagano, Maura Casadio, and Ilana Nisky. 2021. Integrating tactile feedback technologies into home-based telerehabilitation: opportunities and challenges in light of COVID-19 pandemic. Frontiers in Neurorobotics 15 (2021), 617636.

[27] Yutaro Hirao and Takashi Kawai. 2018. Augmented cross-modality: Translating the physiological responses, knowledge and impression to audio-visual information in virtual reality. Electronic Imaging 31 (2018), 1–8.

[28] Pierpaolo Iodice, Giuseppina Porciello, Ilaria Bufalari, Laura Barca, and Giovanni Pezzulo. 2019. An interoceptive illusion of effort induced by false heart-rate feedback. Proceedings of the National Academy of Sciences 116, 28 (2019), 13897–13902.

[29] Susanne M Jaeggi, Martin Buschkuehl, Walter J Perrig, and Beat Meier. 2010. The concurrent validity of the N-back task as a working memory measure. Memory 18, 4 (2010), 394–412.

[30] David Jones, Shiva Ghasemi, Denis Gračanin, and Mohamed Azab. 2023. Privacy, safety, and security in extended reality: user experience challenges for neurodiverse users. In International Conference on Human-Computer Interaction. Springer, 511–528.

[31] Lynette A Jones, Jacquelyn Kunkel, and Erin Piateski. 2009. Vibrotactile pattern recognition on the arm and back. Perception 38, 1 (2009), 52–68.

[32] Anthony D Jose and D Collison. 1970. The normal range and determinants of the intrinsic heart rate in man. Cardiovascular research 4, 2 (1970), 160–167.

[33] Idin Karuei, Karon E MacLean, Zoltan Foley-Fisher, Russell MacKenzie, Sebastian Koch, and Mohamed El-Zohairy. 2011. Detecting vibrations across the body in mobile contexts. In Proceedings of the SIGCHI conference on Human factors in computing systems. 3267–3276.

[34] Susan J Lederman and Roberta L Klatzky. 2009. Haptic perception: A tutorial. Attention, Perception, & Psychophysics 71, 7 (2009), 1439–1459.

[35] Alexander Lischke, Rike Pahnke, Anett Mau-Moeller, and Matthias Weippert. 2021. Heart rate variability modulates interoceptive accuracy. Frontiers in Neuroscience 14 (2021), 612445.

[36] Jennifer K MacCormack, Adrienne S Bonar, and Kristen A Lindquist. 2023. Interoceptive beliefs moderate the link between physiological and emotional arousal during an acute stressor. Emotion (2023).

[37] Tiago V Maia and James L McClelland. 2004. A reexamination of the evidence for the somatic marker hypothesis: What participants really know in the Iowa gambling task. Proceedings of the National Academy of Sciences 101, 45 (2004), 16075–16080.

[38] Steve R Makkar and Jessica R Grisham. 2013. Effects of false feedback on affect, cognition, behavior, and postevent processing: the mediating role of self-focused attention. Behavior therapy 44, 1 (2013), 111–124.

[39] JA Menyhart and PJ Gleary. 1986. False feedback potency and subject fear level as factors in attributions of emotion. Australian Journal of Psychology 38, 2 (1986), 133–144.

[40] Nasir H Naqvi and Antoine Bechara. 2009. The hidden island of addiction: the insula. Trends in neurosciences 32, 1 (2009), 56–67.

[41] Nasir H Naqvi and Antoine Bechara. 2010. The insula and drug addiction: an interoceptive view of pleasure, urges, and decision-making. Brain Structure and Function 214 (2010), 435–450.

[42] David Nunan, Gavin RH Sandercock, and David A Brodie. 2010. A quantitative systematic review of normal values for short-term heart rate variability in healthy adults. Pacing and clinical electrophysiology 33, 11 (2010), 1407–1417.

[43] Jiapu Pan and Willis J Tompkins. 1985. A real-time QRS detection algorithm. IEEE transactions on biomedical engineering 3 (1985), 230–236.

[44] Olga Pollatos, Beate M Herbert, Ellen Matthias, and Rainer Schandry. 2007. Heart rate response after emotional picture presentation is modulated by interoceptive awareness. International Journal of Psychophysiology 63, 1 (2007), 117–124.

[45] Roope Raisamo, Katri Salminen, Jussi Rantala, Ahmed Farooq, and Mounia Ziat. 2022. Interpersonal haptic communication: review and directions for the future. International journal of human-computer studies 166 (2022), 102881.

[46] Lizawati Salahuddin, Jaegeol Cho, Myeong Gi Jeong, and Desok Kim. 2007. Ultra short term analysis of heart rate variability for monitoring mental stress in mobile settings. In 2007 29th annual international conference of the ieee engineering in medicine and biology society. IEEE, 4656–4659.

[47] Suji Sathiyamurthy, Melody Lui, Erin Kim, and Oliver Schneider. 2021. Measuring Haptic Experience: Elaborating the HX model with scale development. In 2021 IEEE World Haptics Conference (WHC). IEEE, 979–984.

[48] Rainer Schandry. 1981. Heart beat perception and emotional experience. Psychophysiology 18, 4 (1981), 483–488.

[49] Christian Scharinger, Alexander Soutschek, Torsten Schubert, and Peter Gerjets. 2017. Comparison of the working memory load in N-back and working memory span tasks by means of EEG frequency band power and P300 amplitude. Frontiers in human neuroscience 11 (2017), 6.

[50] Takeshi Shimizu and Hiroko Norimatsu. 2005. Detection of invariants by haptic touch across age groups: Rod length perception. Perceptual and motor skills 100, 2 (2005), 543–553.

[51] Keisuke Suzuki, Sarah N Garfinkel, Hugo D Critchley, and Anil K Seth. 2013. Multisensory integration across exteroceptive and interoceptive domains modulates self-experience in the rubber-hand illusion. Neuropsychologia 51, 13 (2013), 2909–2917.

[52] Chiew Seng Sean Tan, Johannes Schöning, Kris Luyten, and Karin Coninx. 2014. Investigating the effects of using biofeedback as visual stress indicator during video-mediated collaboration. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. 71–80.

[53] Andreia Valente, Daniel Simoes Lopes, Nuno Nunes, and Augusto Esteves. 2022. Empathic aurea: exploring the effects of an augmented reality cue for emotional sharing across three face-to-face tasks. In 2022 IEEE conference on virtual reality and 3D user interfaces (VR). IEEE, 158–166.

[54] Natalie S Werner, Stefan Duschek, Michael Mattern, and Rainer Schandry. 2009. Interoceptive sensitivity modulates anxiety during public speaking. Journal of Psychophysiology 23, 2 (2009), 85–94.

[55] Natalie S Werner, Katharina Jung, Stefan Duschek, and Rainer Schandry. 2009. Enhanced cardiac perception is associated with benefits in decision-making. Psychophysiology 46, 6 (2009), 1123–1129.

[56] Christopher D Wickens. 2002. Multiple resources and performance prediction. Theoretical issues in ergonomics science 3, 2 (2002), 159–177.

[57] Julian Wölk, Stefan Sütterlin, Stefan Koch, Claus Vögele, and Stefan M Schulz. 2014. Enhanced cardiac perception predicts impaired performance in the Iowa Gambling Task in patients with panic disorder. Brain and behavior 4, 2 (2014), 238–246.

[58] Mingdi Xu, Takeshi Tachibana, Nana Suzuki, Eiichi Hoshino, Yuri Terasawa, Norihisa Miki, and Yasuyo Minagawa. 2021. The effect of haptic stimulation simulating heartbeats on the regulation of physiological responses and prosocial behavior under stress: The influence of interoceptive accuracy. Biological Psychology 164 (2021), 108172.

[59] Clint Zeagler. 2017. Where to wear it: functional, technical, and social considerations in on-body location for wearable technology 20 years of designing for wearability. In Proceedings of the 2017 ACM International Symposium on Wearable Computers. 150–157.