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Exploring the Emotional Effects of Enhanced Interoception via Heartbeat-synchronized Haptic Feedback

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This study examines how amplifying real-time heartbeat feedback affects emotion regulation. Accurate heartbeat perception—a key facet of cardiac interoception—has been linked to emotional awareness and mental well-being, yet the causal role of interoceptive feedback in emotion regulation remains underexplored. We empirically tested whether making heart rate signals more perceptible through wearable haptic feedback could facilitate implicit emotion regulation during emotionally evocative experiences. Using a custom Fitbit-based system, thirty participants received real-time, sham, or no heartbeat-synchronized vibrations while viewing fear- and amusement-inducing film clips. Interoceptive accuracy, emotional disturbance, and the linguistic complexity of emotion descriptions were measured. Exploratory analyses showed that real-time feedback reduced emotional disturbance during fear stimuli, especially among individuals attentive to bodily sensations, though effects did not remain significant after multiple comparisons correction. Feedback primarily modulated arousal rather than valence and did not significantly affect heartbeat counting or linguistic complexity. As one of the first causal, empirical investigations of interoceptive feedback and emotion regulation, this work identifies boundary conditions for its effectiveness and offers insights for designing personalized, interoception-aware wearable technologies.

CCS Concepts: • **Human-centered computing → Empirical studies in ubiquitous and mobile computing**; *Haptic devices*; Empirical studies in HCI; Interaction design theory, concepts and paradigms.

Additional Key Words and Phrases: Interoception, Emotion regulation, Haptic feedback, Heartbeat-synchronized feedback, Wearable technology, Physiological computing, Emotional awareness, Affective computing, Human–computer interaction

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1 INTRODUCTION

1.1 The Role of Interoception in Mental Health and Emotion Regulation

With increasing evidence that mental health disorders are associated with interoceptive deficits, interest in their causal relationship has grown in recent years. *Interoception*—the ability to perceive, interpret, and regulate internal bodily signals—has been theorized to play a role in recognizing emotions and enabling self-regulation grounded in physiological and emotional awareness [8, 58]. A growing body of psychological and Human-Computer Interaction (HCI) literature highlights the role of interoception not just in emotion identification, but in *emotion regulation* [50, 54, 58]. Within this framework, individuals with poor interoceptive ability may struggle to identify and regulate their emotional and physiological states, contributing to a range of mental health challenges. This hypothesis is supported by findings that individuals with high levels of *alexithymia*—a difficulty in identifying, describing, and regulating emotions—often exhibit impaired interoceptive function [8], and alexithymia itself has been identified as a risk factor for poor mental health [36].

What specific role does interoception play in mental health, and why is it important? A growing body of research suggests that *interoceptive information*—signals about the internal state of the body—is foundational for emotional and behavioral self-regulation. According to the Gross Process Model of Emotion Regulation (ER) [22], regulation begins with an *identification* phase, in which individuals decide to start the regulation process. This is followed by the *selection* of ER strategy, *implementation*, and *monitoring* of regulatory strategies (Fig. 1).

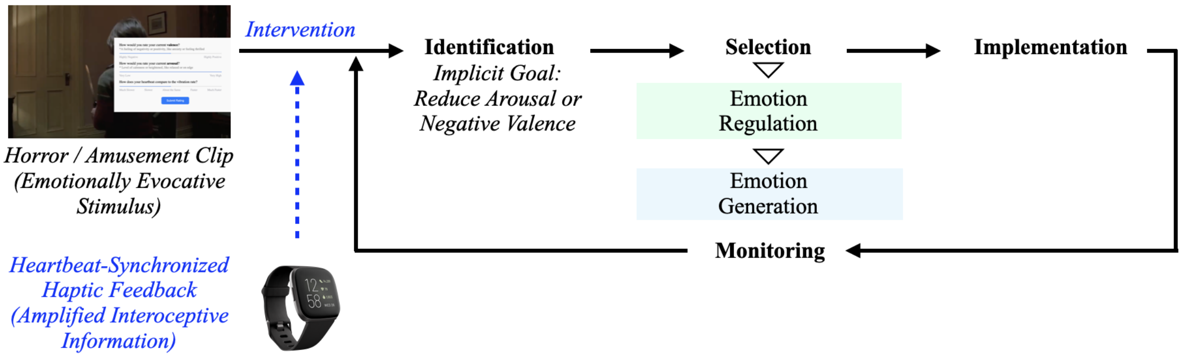

Fig. 1. Conceptual model adapted from Gross's Process Model of Emotion Regulation [22], illustrating how heartbeat-synchronized haptic feedback amplifies interoceptive information during emotionally evocative stimuli. Solid lines and bolded text denote the original model, and dotted lines and italicized labels indicate extensions that implicitly activate a goal to reduce arousal or negative valence, facilitating emotion regulation.

Interoceptive signals are particularly crucial during the identification and monitoring phases, as they provide the somatic cues necessary to recognize one's current emotional state [11]. Recent findings support the view that accurate perception and interpretation of bodily states enable individuals to detect affective changes that may require regulation [28]. When these processes are impaired, as in alexithymia, individuals may fail to recognize when regulation is needed or apply strategies inappropriately, leading to dysregulated emotional responses such as emotional blunting or outbursts [8, 34, 41]. Such disruptions have been associated with increased vulnerability to anxiety, depression, and other affective disorders [26]. To understand how such difficulties emerge, it is important to examine how interoception supports emotion regulation processes over time.

1.2 Amplifying Interoception for Emotion Regulation

The majority of existing research has focused on correlational studies linking interoceptive function with mental health, typically by measuring well-being alongside tests of interoceptive function. *Interoceptive accuracy* is commonly assessed using heartbeat perception tasks, which provide a non-invasive estimate of one's ability to perceive internal bodily signals. Despite this evidence of correlation, relatively little research has addressed whether improving interoceptive ability can causally improve emotional regulation or well-being. Some support for this comes from the success of body-focused psychotherapeutic interventions in which individuals are trained to attend to and reinterpret interoceptive signals [27]. However, such interventions often involve complex multi-component processes, including attentional training, cognitive reappraisal, and self-regulation, which makes it difficult to identify the active mechanism by which it improves mental health (Fig. 1).

To address these challenges, recent work [2, 16] has turned toward technologies that can enhance interoception more directly. Advances in wearable devices allow for real-time physiological feedback, offering a promising avenue for amplifying internal signals. A more direct way to enhance interoceptive ability is to amplify interoceptive information itself. While *explicit emotion regulation* refers to consciously and effortfully enacted regulatory processes, *implicit emotion regulation* refers to those that are activated automatically or outside of conscious awareness, often through the modulation of internal attention or perception [6, 50]. This distinction is particularly relevant in HCI, where ambient and non-intrusive systems may support regulation not by teaching strategies, but by increasing bodily awareness during emotionally salient moments.

Yet despite growing interest, several limitations remain. Most prominently, while much research has explored the effects of false heart rate feedback on emotion, arousal, and performance [9, 10, 21], little research has focused on the effects of making the user's true heart rate more perceptible. Most prior work has focused on stress regulation during performance-based tasks [32] or on heartbeat detection during resting conditions [42], rather than during emotionally evocative situations. Furthermore, interventions often target mental health outcomes such as anxiety or depression [1, 3], without carefully examining the intermediate mechanisms that may drive the change—whether through increased bodily awareness, improved emotion recognition, or enhanced regulation.

One promising but underexplored hypothesis is that real-time interoceptive feedback can act as a form of implicit emotion regulation. Few studies have tested whether physiological cues delivered in real time can modulate affective disturbance without explicitly instructing users to regulate their emotions. Building on the framework by Braunstein et al.[6] and Slovak et al.[50], we argue that such interventions may activate chronically held regulatory goals (e.g., reducing emotional discomfort), while engaging attentional and perceptual mechanisms that implicitly support regulation.

To investigate this possibility, we developed a smartwatch-based system that uses a photoplethysmography (PPG) sensor to detect heart rate and deliver haptic vibrations synchronized with the user's heartbeat. This system provides an "amplified" cardiac signal that may help users monitor and become more aware of their bodily state in real time. We explore whether amplifying interoceptive information in real time may support regulation during emotionally intense experiences. Specifically, we apply this system during the viewing of horror film clips, which serve as reliable but safe fear-inducing stimuli. Horror films present mediated danger that can trigger transient fear responses while prompting viewers to modulate their emotional reactions. This approach aligns with Excitation-Transfer Theory [59], which suggests that individuals seek to prevent overstimulation by regulating emotional carryover between arousing events.

In addition to addressing conceptual gaps, our study responds to methodological limitations. Existing interventions often rely on static, pre–post measures of emotional state, overlooking the dynamic fluctuations that unfold during affective experiences [**?**]. Emotional responses are inherently dynamic, and capturing how physiological feedback influences moment-to-moment emotional changes is critical for evaluating the efficacy of interoceptive interventions. While recent studies suggest that congruent bodily feedback may enhance emotion recognition [57], few have tested whether strengthening attunement to bodily signals dynamically alters emotional disturbance during evocative experiences.

Another key consideration is the distinction between *interoceptive accuracy* (objective detection of bodily signals) and *interoceptive awareness* (subjective sensitivity and reflection). Growing recognition that these are distinct but related constructs [19] underscores the need for a more holistic approach. Enhancing bodily awareness may support emotional resilience even in the absence of measurable improvements in accuracy, emphasizing the importance of evaluating both subjective and objective dimensions of interoception. Moreover, individual differences in their baseline interoception abilities remain underexplored. Research suggests that interoceptive sensibility and self-regulation abilities moderate individuals' responses to feedback [47], yet many studies treat participants as a homogeneous group. These individual traits may shape both the perception and impact of interoceptive interventions and must be considered to understand for whom and under what conditions these systems are most effective.

By designing an experiment that manipulates a single aspect of interoceptive function, or the perceptibility of accurate heart rate information, we aim to isolate and better understand the mechanisms by which interoceptive feedback supports emotional regulation. This work contributes to a more nuanced understanding of how real-time physiological signals can serve as tools for implicit regulation and lays the groundwork for future mental health interventions that adapt to individual needs and momentary states.

1.3 Exploring Real-time Interoceptive Feedback for Implicit Emotion Regulation

To address these gaps, we conducted one of the first studies to examine the causal relationship between interoceptive accuracy and emotion regulation during emotionally evocative experiences. Specifically, we frame our work as exploring whether real-time, true heartbeat feedback can serve as an implicit emotion regulation mechanism—modulating emotional disturbance in high-arousal scenarios without explicit instruction. To our knowledge, this experiment is also the first to investigate the emotional effects of real-time heart rate–synchronized feedback—rather than the more commonly studied slower or false feedback—by investigating the effect of increasing perception of one's actual heart rate on emotion regulation.

To test the effects of interoceptive feedback on emotion regulation, we used an emotion induction task in which participants viewed standardized fear-inducing film clips and reported their mood before and after each clip. Similar paradigms [24] have been used to study fear regulation based on the principle that viewing frightening stimuli in a safe environment elicits two concurrent processes: a direct fear response to the stimulus and a prefrontal-driven regulatory response that dampens the fear. This regulatory response is thought to reflect contextual processing—that is, it becomes active when the individual recognizes that a strong fear response is not appropriate, because the stimuli are fictional and the environment is safe [37].

The degree of arousal and valence change [44] following a frightening stimulus can therefore serve as a proxy for contextual fear regulation: the ability to downregulate emotional responses that are disproportionate or unnecessary for the current situation. We used this measure to test whether real-time heart rate feedback, compared to sham feedback, can improve participants' ability to regulate their fear response. As an active control, we also examined responses to amusing clips, which do not elicit fear and thus do not require regulation. This allows us to isolate the specific effects of interoceptive feedback on regulation.

Building on this theoretical foundation, our study aims to advance the understanding of how physiological feedback influences emotional experiences by addressing the following research questions:

- **RQ1: Does real-time heartbeat-synchronized feedback improve bodily awareness or heartbeat detection?** Can a single session of real-time heartbeat feedback significantly improve participants' ability to feel and notice their bodily signals (interoception) measured by increase in heartbeat perceiving ability (interoceptive accuracy)?

- **RQ2: Does improving bodily awareness through feedback help regulate emotions?** Does receiving real-time heartbeat feedback reduce emotional disturbance—measured as the Euclidean distance between pre- and post-stimulus ratings along both valence and arousal dimensions—during emotionally evocative stimuli?
- **RQ3: Does real-time heartbeat feedback enhance participants' ability to identify and describe their emotions?** Does feedback lead to increased and richer emotional descriptions, reflected in the diversity and complexity of emotion-related terms participants use?
- **RQ4: How do individual differences in baseline interoceptive traits affect the impact of feedback?** Do participants' baseline interoceptive awareness and self-regulation abilities moderate the effects of real-time heartbeat feedback on bodily awareness, emotion identification, and emotion regulation? Additionally, does baseline interoceptive sensitivity influence how participants differentiate between the effects of real versus sham heartbeat feedback?

2 RELATED WORK

2.1 Physiological Systems for Emotional Support

Human-Computer Interaction (HCI) research has increasingly explored emotionally intelligent systems that use physiological data to support emotion regulation. Early interventions emphasized mindfulness [9, 21], while subsequent systems integrated biofeedback to help users manage stress through direct physiological modulation [55]. A key research area involves physiological synchronization, where external feedback mirrors users' real-time biosignals to foster internal awareness and regulation [25]. Recent systems have leveraged haptic and auditory modalities to guide breathing and reduce stress. BrightBeat used rhythmic haptic cues to foster calmness and focus [21], and CalmCommute delivered slow breathing prompts to drivers [4]. Beyond stress reduction, physiological mirroring has also supported social connection. EmbER provided real-time heartbeat and breathing patterns from narrators, enhancing empathic connection [29]. Likewise, Winters et al.[57] found that listening to expressive heartbeat signals improved emotion recognition.

A growing body of work examines cardiac-based feedback for emotion regulation. EmotionCheck and BoostMeUp demonstrated that false, slowed-heartbeat feedback can reduce anxiety and improve task performance under pressure [9, 10], but these systems rely on deceptive or non–real-time inputs. HeartBit introduced a real-time, heartbeat-synchronized haptic system to increase interoceptive attention [43] but did not assess emotional outcomes. More recent studies have begun to fill this gap: Dobrushina et al. (2024) found that real-time haptic heartbeat feedback enhanced interoceptive accuracy and confidence, while Valente et al. (2024) showed that feedback location modulates heart rate and user preference. Still, this subdomain rarely examines emotional outcomes in emotionally evocative contexts, and to our knowledge, no prior work has explicitly positioned cardiac feedback as a form of implicit emotion regulation.

Recent HCI research calls for more nuanced understandings of how technology can support emotion regulation—particularly through experiential, real-time, and situated interventions. Slovak et al. [50] argue that interventions should be evaluated not only for their psychological outcomes but also for how they engage users' embodied and implicit regulatory processes. Our work extends this line by examining whether real-time cardiac feedback can serve as an implicit emotion regulation mechanism, activated during high-arousal moments elicited by horror film stimuli.

2.2 Interoceptive Accuracy and Emotional Well-being

Interoception plays a foundational role in emotional awareness, regulation, and mental health [11]. Individuals with higher interoceptive accuracy, commonly assessed via heartbeat perceiving tasks, tend to exhibit greater emotional granularity, improved emotion regulation skills, and increased psychological resilience [19, 38]. These associations have informed the development of interventions aimed at enhancing interoceptive processing as a pathway to emotional well-being.

Interoceptive ability can be measured by measuring a subject's accuracy in perceiving a signal within the body; for instance some of the most commonly used interoception tests involve heartbeat perception. In these tests, subjects are asked to count their heartbeats over a fixed period without physically taking their pulse. The discrepancy between counted and actual heartbeats or the sensitivity to changes in heart rate provides a metric of interoceptive accuracy [7]. Heartbeat counting tasks are widely used due to their simplicity and non-intrusiveness, although other approaches—such as questionnaires assessing interoceptive sensibility or tasks involving sensitivity to other physiological signals—are also employed [14].

However, the most widely used assessment—the heartbeat counting task (HCT)—has faced increasing scrutiny. Research suggests that HCT performance may be influenced by non-interoceptive factors, such as prior beliefs about typical heart rates, cognitive estimation strategies, or individual differences in cardiorespiratory fitness, thereby calling into question its validity as a measure of true interoceptive accuracy [12, 17]. In response, alternative metrics such as heartbeat-evoked potentials (HEPs) have been proposed to offer more objective neural indices of interoceptive processing, particularly during emotionally charged tasks [53].

Yet, most existing studies assess interoception in static or resting contexts, often neglecting how interoceptive signals dynamically interact with emotional experiences in real-world or emotionally evocative scenarios. This is a critical limitation, as the demand for effective emotional regulation strategy selection is highest when affective stimuli are intense or unexpected [48, 49]. Moreover, while accuracy is commonly targeted, subjective interoceptive awareness—how individuals interpret and reflect on bodily signals—may play an equally critical role in emotional self-regulation. Notably, even in the absence of accurate signal detection, enhanced bodily attention may activate self-soothing responses or implicit regulation goals [6]. Thus, interoceptive processes should be studied both as perceptual capacities and as modulators of emotion.

2.3 Summary of Research Gaps

While prior work highlights the feasibility of physiological biofeedback and interoceptive training, several limitations constrain their applicability to real-world emotional regulation:

- Although correlational studies suggest that greater interoceptive accuracy is associated with improved emotion regulation, few studies have directly tested whether amplifying interoceptive signals (i.e., making them more perceptible) causally enhances emotion regulation ability.
- While false or static heartbeat feedback has been shown to modulate anxiety and task performance, relatively few studies have directly examined the emotional effects of real-time, heartbeat-synchronized feedback that mirrors users' actual physiological states.
- Most interoceptive interventions have been tested in low-arousal or task-focused settings (e.g., resting-state or performance tasks), rather than in emotionally evocative contexts with higher regulatory demands.
- Although individual differences such as interoceptive sensibility and self-regulation capacity are known to moderate intervention outcomes, many studies still analyze participants as a homogeneous group, limiting insight into personalized effects.
- Additionally, few studies have framed these systems through the lens of implicit emotion regulation. There remains a gap in understanding how real-time feedback—delivered without explicit instruction—might modulate emotional disturbance through attention and perception-based pathways.

Our study directly addresses these gaps by thoroughly examining how real-time, heartbeat-synchronized haptic feedback influences interoceptive awareness, emotion identification, and implicit emotional regulation in emotionally charged settings. We analyze participants' ability to modulate their affective responses when presented with emotionally evocative clips in a safe, controlled environment. By combining dynamic emotional disturbance metrics with both subjective and objective interoceptive measures, and accounting for individual baseline traits, we aim to advance understanding of how physiological feedback supports emotion regulation in emotionally evocative setting with mediated danger stimuli.

3 METHODOLOGY

3.1 System Design

3.1.1 Haptic Wristband Hardware. We developed a custom app running on the Fitbit Versa 2 smartwatch to monitor participants' heartbeats and provide real-time vibrational heart rate feedback. The feedback was either synchronized with the participants' true heart rate or simulated, depending on the study condition: real, sham, or no feedback. The Fitbit was chosen for its off-the-shelf accessibility and ability to deliver customizable vibration feedback while continuously monitoring heart rate. Haptic feedback was transmitted through the wristband, and the vibrations were subtle—comparable to the gentle alarm vibrations of common digital devices. The Fitbit Versa provides zero-latency heart rate readings at a minimum frequency of 10 Hz using photoplethysmography (PPG). While this method is non-clinical and subject to artifacts (e.g., motion-induced noise), it has been shown to provide sufficient temporal resolution for perceptual feedback tasks. Previous validation studies report ± 4–9 bpm error margins [18], which we considered acceptable given that the goal in this study was for participants to perceive relative accelerations and decelerations in heart rate over a period of minutes.

In the sham feedback condition, participants received vibration feedback that mimicked a heartbeat pattern but was not synchronized with their own. To avoid confounding effects associated with slower or faster artificial heartbeats—known to influence perception and emotional state in prior research—we used a single pre-recorded heartbeat from a random subject. This sequence was not clinically altered and could be faster, slower, or similar to participants' real-time heartbeats. In the no-feedback condition, participants wore the device without receiving any vibrations; only their real heartbeats were recorded.

3.1.2 Study Interface. We developed a custom digital interface (Fig. 2) to administer tasks, record participant responses, and manage randomized feedback conditions. The interface automated the experimental flow, including video playback, slider-based emotional and interoceptive ratings, the heartbeat perception task, and open-ended response collection.

3.1.3 Emotionally-evocative Stimuli. We sourced our emotionally evocative stimuli from the standardized FilmStim dataset [46], which contains emotion-labeled segments identified through prior crowd-sourced emotion tagging. We specifically selected clips tagged with the emotions $Fear$ and $Amusement$ to represent distinct emotional contexts. *Fear* was chosen as the primary target emotion due to its high arousal and negative valence, which are closely linked to heightened interoceptive and bodily awareness. *Amusement* served as a high-arousal, positive-valence counterpart to help regulate participants' emotional states and act as a control condition for comparison, because it does not require participants to engage in emotional regulation. In addition, the amusement clips acted as emotional resets between fear exposures to prevent habituation or desensitization.

Since individual clips varied in length from 2 to 5 minutes, we concatenated them to form blocks approximately 10 minutes in duration. Clips were randomly selected based on duration to create combinations of fear and amusement clips that aggregated as closely as possible to the 10-minute target. This ensured that participants had sufficient time to engage with the stimuli and experience the associated vibration conditions, while maintaining consistency across the blocks. Each block followed the same structure of either fear–amusement–fear (Block 1 and 3) or fear–amusement–fear–fear (Block 2), depending on the clip durations available. Block 2 included an additional fear clip to compensate for the shorter duration of available amusement clips and maintain the overall 10-minute target length.

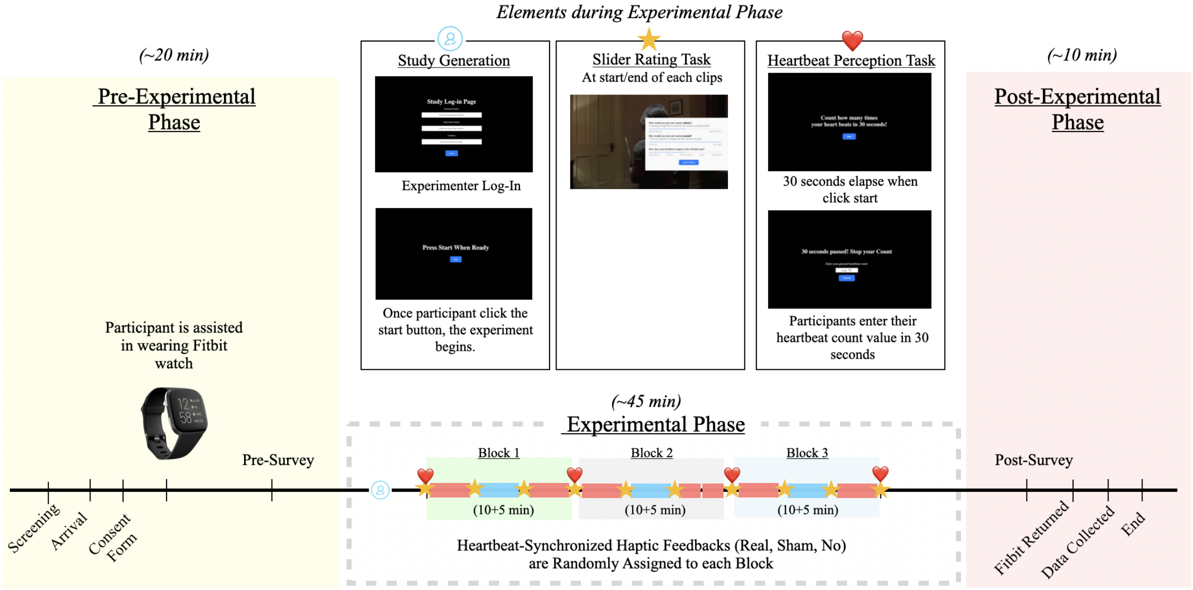

Fig. 2. Diagram of the study protocol, from the pre-experimental phase to the experimental phase. Each block represents one of the three conditions: Real Heartbeat Feedback, Sham Heartbeat Feedback, or No Feedback. Each block includes approximately 10 minutes of video clips and a series of tasks—a slider rating task (star icon), a heartbeat perception task (heart icon), and a self-report task (person icon)—which together take about 5 minutes. In each block, participants watch fear stimulus clips (red rectangles) interleaved with amusement stimulus clips (blue rectangles), sourced from the standardized FilmStim dataset [46].

Amusement clips were intentionally placed in the middle of each block to serve as a buffer between fear stimuli. Such placement was intended to "reset" participants' affective states and minimize emotional carryover, enabling clearer comparisons between fear and non-threatening emotional responses. By including both fear and amusement—two emotions that are high arousal but opposite in valence—we aimed to determine whether interoceptive feedback effects were specific to fear or generalized across high-arousal conditions. If effects appeared for both, it would suggest a broader modulation by arousal; if limited to fear, it would point to specificity for high-arousal, negatively valenced (or threatening) experiences.

As in previous emotion-regulation experiments, horror film clips are chosen to elicit transient high-arousal states while participants remain physically safe. This contrast is thought to elicit implicit regulatory processes: individuals may experience fear yet internally down-regulate their response due to contextual safety cues, such as recognizing the threat is not real [24, 37, 59]. This design thus enables us to explore whether physiological feedback supports implicit regulation of arousal generally or specifically buffers aversive emotion.

3.2 Measurements

3.2.1 Trait Measures. Trait interoceptive sensibility was measured with the Multidimensional Assessment of Interoceptive Awareness (MAIA-2) [31] and the Interoceptive Confusion Questionnaire [8]. We assessed baseline emotion regulation and emotional reactivity through the Difficulties in Emotion Regulation Scale (DERS-16) [5].

3.2.2 Interoceptive Accuracy. To assess interoceptive accuracy, participants completed the Heartbeat Perception Task [19] after each block. They were instructed to focus on their internal sensations without palpating their pulse. Participants clicked the start button to begin a 30-second counting period, during which they silently counted their heartbeats until the interface automatically indicated the end of the interval. Afterward, they entered their counted number of heartbeats into the interface.

3.2.3 Qualitative Responses. Participants also answered open-ended questions following each block: "Please list all the emotions you experienced while watching the films," and "Were there any specific moments in the videos that elicited a strong emotional reaction? If so, which moments?" Responses were analyzed for emotional sentiment, richness, and complexity. We measured emotional complexity by coding qualitative responses using Plutchik's Wheel of Emotions [39]. Primary emotions (e.g., fear, joy) and secondary emotions (e.g., anxiety, amusement, relief) were counted for each participant, and the complexity score was defined as the ratio of secondary to primary descriptors. This approach aligns with prior affective science work linking emotional granularity to interoceptive and regulatory capacities. Emotional granularity is a known marker of emotion regulation ability, particularly in situations where regulation is not explicitly instructed but instead emerges from internal attentional shifts [6].

3.3 Study Procedures

3.3.1 Participants. We recruited 30 healthy adults (16 female; M_{age} = 23.11, SD = 10.18) through campus mailing lists. Inclusion criteria required normal or corrected-to-normal vision and hearing and no history of heart arrhythmia. All participants provided informed consent and received a $20 Amazon gift card as compensation. The study protocol was approved by the Institutional Review Board (IRB). Four participants were excluded due to technical issues, resulting in a final sample of 26.

3.3.2 Pre-experimental Phase. All sessions took place in a quiet laboratory room. Upon arrival, a trained facilitator introduced the study and explained key affective dimensions (arousal and valence). Participants wore a Fitbit watch on their non-dominant wrist, which delivered haptic feedback in sync with their heartbeat. The facilitator explained that this vibration was aligned with their real heartbeat to help them attune to their internal bodily signals. While wearing the device, participants completed a demographics form and the trait measures described in Section 3.2.1. We did not instruct users to regulate their emotions explicitly, because our goal is to investigate whether making their internal signals more perceptible through real-time feedback might activate implicit regulatory processes—such as bodily grounding or attention modulation—during affective experiences. This procedure ensured that participants understood the tasks but were not primed for deliberate regulation.

3.3.3 Experimental Phase. The experiment was structured into three blocks of 10 minutes in duration. True feedback (TF) is the condition where the fitbit-provided heart rate data accurately reflects the participant's actual physiological state, sham feedback (SF) is where the Fitbit display deliberately shows incorrect heart rate information, decoupled from the participant's true cardiovascular activity, and no feedback (NF) is the condition in which participants receive no heart rate data from the Fitbit device at all. Each participant experienced all three feedback conditions (TF, SF, NF) in a randomized order. Within each block, participants completed a fixed sequence of tasks.

Participants rated their arousal and valence periodically during video playback using continuous scale slider inputs ranging from -2 to 2, with precision up to two decimal places, following the circumplex model of affect [44]. Participants also assessed their awareness of heartbeat feedback. In the TF and SF conditions, they answered: "How does your heartbeat compare to the vibration rate?" In the NF condition, they were asked: "How fast is your current heartbeat compared to before?" Responses were recorded on a 5-point Likert scale from "much slower" to "much faster." The video paused automatically for ratings. The questions differed across conditions to match participants' perceptual experience. In TF and SF, participants received vibrational input and could directly compare the perceived versus actual heartbeat. In the NF condition, no feedback was present, so the comparative frame shifted to internal self-reference over time (i.e., "now" vs. "before"). This adjustment ensured that all conditions probed interoceptive sensitivity while maintaining perceptual plausibility.

At the end of each block, participants completed the heartbeat perception task and qualitative emotion questions. The facilitator then configured the Fitbit for the next feedback condition.

3.3.4 Post-experimental Phase. After completing all three blocks in the Experimental Phase, participants filled out a final questionnaire assessing the usability of the feedback system. The session concluded with debriefing and Fitbit device removal.

4 ANALYSIS

4.1 Interoceptive Accuracy (H1)

To test the first hypothesis, which proposed that receiving real-time haptic feedback improves interoceptive accuracy compared to sham and no-feedback conditions, we analyzed participants' responses to the heartbeat counting task in the true feedback (TF), sham feedback (SF), and no feedback (NF) conditions. During this task, participants estimated the number of heartbeats they experienced over a 30-second interval. We calculate the true number of heartbeats using the average heart rate of the participant during the same interval, as recorded by the Fitbit.

Interoception error was defined as the error in estimating heartbeats, using the formula:

$$\text{Error}_{\text{condition}} = \frac{|\text{Participant's Estimate}_{\text{condition}} - \text{Real Heartbeat Count}_{\text{condition}}|}{\text{Real Heartbeat Count}_{\text{condition}}} \tag{1}$$

This relative error metric reduces bias introduced by individual differences in heart rate and aligns with common practices in psychophysiology research.

To analyze differences in interoceptive accuracy, a repeated-measures analysis of variance (ANOVA) was conducted. This analysis examined the main effect of feedback condition on interoceptive accuracy and was followed by post-hoc pairwise comparisons with Bonferroni corrections to determine which conditions differed significantly.

4.2 Emotion Regulation and Arousal–Valence Disturbance (H2)

The second hypothesis proposed that accurate real-time haptic feedback reflecting participants' heartbeats would attenuate emotional responses to fear-inducing stimuli, while having minimal effects on responses to amusement stimuli that induced positive valence in comparison.

Participants' emotional responses to the stimuli, which we define as disturbance, were calculated as the Euclidean distance between their self-reported slider ratings of arousal and valence at the beginning and end of each film excerpt [40]. The sliders allowed continuous values of measurement for valence and arousal, from highly negative (-2) to highly positive (2). We modeled changes in emotions induced by watching the clips as shifts in arousal/valence space, which is a commonly used way to model emotions [20, 35, 52].

We first calculated the difference in arousal and valence ratings induced by watching a clip, which we define as *Valence difference* and *Arousal Difference*. Participants rated their arousal and valence on a -2 to 2 scale before and while watching the clip, and the difference was calculated.

$$\text{Difference} = \text{Likert rating after watching clip} - \text{Likert rating before watching clip} \tag{2}$$

We then calculated the *disturbance* as the distance moved in arousal and valence space between the pre-clip and post-clip ratings using the Euclidean distance.

$$\text{Disturbance} = \sqrt{\text{Valence difference}^2 + \text{Arousal difference}^2} \tag{3}$$

The disturbance, therefore, reflects the degree to which participants' emotional state was affected by the clip.

To calculate changes in valence and arousal for the first fear clip in Block 1, we computed the difference between the end and start measurements for that clip. For Clip 1, we squared the sum of the valence and arousal differences to obtain a disturbance score. We then summed the disturbance scores from both fear clips (Clip 1 and Clip 3 in Block 1) to define the total fear disturbance for Block 1 (Fig. 2).

To compare the effects of feedback condition and type of stimuli (fear/amusement) on emotional disturbance, we calculated disturbance for each Fear and Amusement stimulus and performed repeated measures analysis of variance (ANOVA). This analysis examined the main effects of the feedback condition and the type of stimuli, as well as the interaction between these factors (Condition × Stimuli Type).

4.3 Effects of Feedback on Emotion Identification and Awareness (H3)

To test the hypothesis that participants who received accurate haptic feedback would exhibit greater emotional awareness and use more complex and diverse emotional language, we analyzed participants' open-ended responses to the questions described in Section 3.2.3. We used the NRC Emotion Lexicon [33] to identify words associated with emotion, while TextBlob [1] was used for sentiment analysis. Emotional complexity was calculated as the ratio of secondary to primary emotions[39].

5 RESULTS

5.1 True heartbeat feedback improved emotional regulation in participants with high body-focused self-regulation ability (H2)

Figure 3 presents the overall distribution of emotional (Valence and Arousal) score differences between before and after watching fear and amusement videos. Feedback condition did not significantly predict overall shifts in arousal nor valence while watching fear clips.

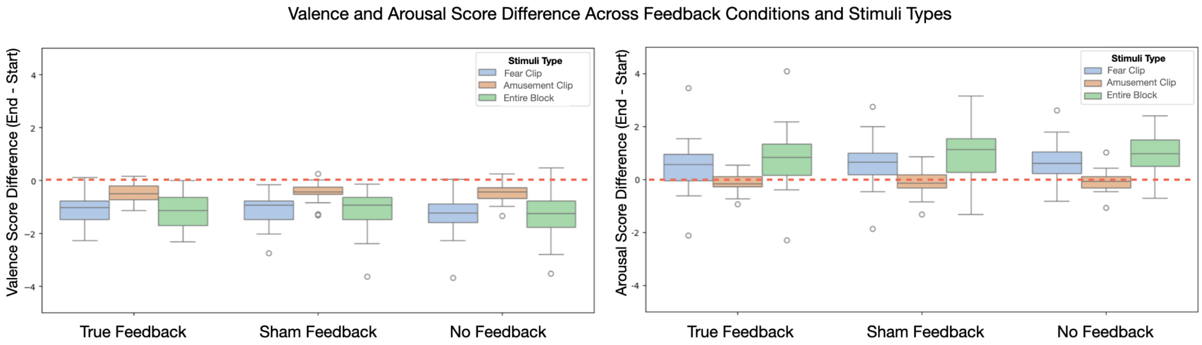

Fig. 3. Video clip-related changes (rating after clip - before clip) in arousal and valence scores across feedback conditions (True Heartbeat Feedback, Sham Heartbeat Feedback, and No Feedback) and film stimuli types (Fear and Amuse). Arousal and valence were rated on a -2 to 2 on a continuous slider scale (-2=low, 2=high) at the start and end of each clip, so the largest possible difference between the pre-clip and post-clip measurements is ±4.

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[1] https://github.com/sloria/TextBlob

To test whether stimulation produced effects in a subset of participants, we performed an exploratory analysis testing for an interaction between stimulation condition and each axis measured in the initial questionnaires. This analysis was performed using a mixed-effects linear model in JMP 18, with participant ID as a random factor and condition, interoceptive confusion score, DERS-16 score, MAIA Noticing, MAIA Not-Distracting, MAIA Not-Worrying, MAIA Attention Regulation, MAIA Emotional Awareness, MAIA Self-Regulation, MAIA Body Listening, and MAIA Trusting axes entered as fixed factors. This is a standard approach [56] which allows for repeated measures comparisons while controlling for individual differences in emotional intensity (e.g., the tendency of some participants to always rate their emotions as more intense than other participants). We also included the interaction terms between condition and individual difference measures as a fixed factor. Because we were interested only in the effects attributable to true interoceptive feedback, we only contrasted true and sham heartbeat feedback, excluding the no-feedback condition from this analysis.

While none of the results from the exploratory analysis were significant when correcting for multiple comparisons using FDR, we did observe several interesting trends. We first tested whether the interaction of stimulation condition and baseline characteristics modulated emotional disturbance to the fear clips. The analysis revealed a significant interaction between feedback condition and MAIA self-regulation scores, F(1, 15.1) = 10.32, uncorrected p = .006, indicating that participants with higher self-regulation scores exhibited lower emotional disturbance in the true heartbeat feedback condition compared to the sham heartbeat feedback condition. Specifically, the interaction term (Self-Regulation × Condition [True Heartbeat Feedback]) had an estimated effect of −2.84 on emotional disturbance (Figure 4, table 1).

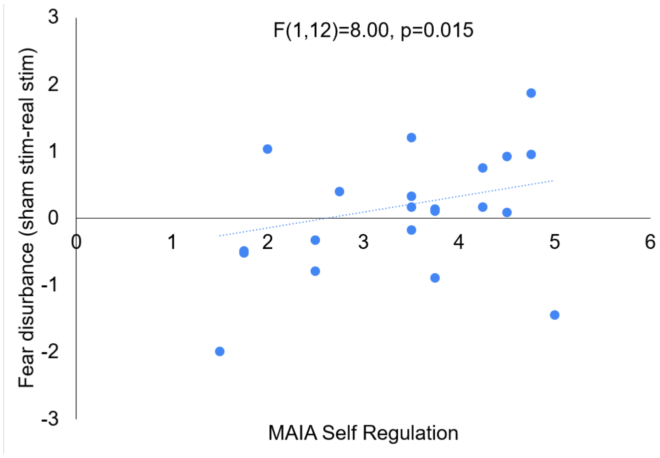

Fig. 4. Interaction of MAIA Self-Regulation scores with feedback condition. The Y axis shows the difference between disturbance from fear clips in the sham heartbeat feedback condition and disturbance in the true heartbeat feedback condition, with positive values indicating a protective effect of true heartbeat feedback (less disturbance in the true heartbeat condition). Statistics are based on fixed parameter outputs from the mixed model. The largest possible difference in disturbance is 4, which is the maximum Euclidean distance possible in the valence/arousal space (which was defined by two sliders ranging from -2 to 2).

Self-regulation*condition also modulated the difference between fear clip disturbance and amusement clip disturbance, such that true heartbeat feedback reduced the difference in response to fear clips versus amusement clips in participants with high self-regulation scores (Table 2, [F(1,12=7.24, uncorrected p=0.02]). These observations suggest that true heartbeat feedback modulated emotional responses specifically under stress-inducing

Table 1. Mixed model terms modulating emotional disturbance from viewing fear videos.

Term	Estimate	Std Error	DFDen	t Ratio	p	FDR p
Noticing	0.57	0.32	12.0	1.75	0.11	0.35
Not-Distracting	0.95	0.38	12.0	2.49	0.03	0.14
Not-Worrying	-1.05	0.39	12.0	-2.72	0.02	0.13
Attention Regulation	-1.65	0.35	12.0	-4.77	0.00	0.00
Emotional Awareness	0.72	0.39	12.0	1.82	0.09	0.34
Self-Regulation	-0.05	0.20	12.0	-0.27	0.79	0.88
Body Listening	0.14	0.22	12.0	0.65	0.53	0.72
Trusting	-0.23	0.21	12.0	-1.12	0.28	0.65
DERS-16_Score	0.39	0.26	12.0	1.52	0.15	0.41
Condition [Real feedback]	-0.09	0.10	12.0	-0.91	0.38	0.66
(Noticing - 3.75) × Condition	-0.06	0.25	12.0	-0.22	0.83	0.88
(Not-Distracting - 3.92424) × Condition	-0.21	0.29	12.0	-0.73	0.48	0.70
(Not-Worrying - 3.80303) × Condition	0.29	0.30	12.0	0.99	0.34	0.65
(Attention Regulation - 3.29221) × Condition	-0.04	0.27	12.0	-0.15	0.88	0.88
(Emotional Awareness - 3.23636) × Condition	0.07	0.30	12.0	0.24	0.81	0.88
(Self-Regulation - 3.38636) × Condition	-0.43	0.15	12.0	-2.83	0.02	0.13
(Body Listening - 3.19697) × Condition	0.13	0.17	12.0	0.76	0.46	0.70
(Trusting - 3.31818) × Condition	0.17	0.16	12.0	1.05	0.31	0.65
(DERS-16_Score - 2.25852) × Condition	0.04	0.20	12.0	0.21	0.84	0.88

conditions (fear clips), rather than causing general emotional dampening by having an effect on amusement clips as well, supporting our hypothesis that interoceptive feedback facilitates targeted emotional regulation.

To further understand how the feedback modulated disturbance, we examined the effects on the two components of disturbance (clip-induced change in valence and clip-induced change in arousal) separately. Self-regulation* condition modulated the change in arousal induced by fear clips (Table 3, [F(1,15.1)=9.34, uncorrected p=0.008]), but it did not modulate the change in valence induced by fear clips (Table 4, [F(1,14.6)=0.004, uncorrected p=0.96]).

5.2 True heartbeat feedback did not significantly increase interoceptive accuracy (H1)

Repeated measures ANOVA did not reveal a statistically significant main effect of the feedback condition on the precision of the interoceptive (F (2, 66) = 1.02, p = 0.37).

The descriptive statistics also indicated that the heart rate count error was lowest in the no feedback condition (mean = 0.59, SEM = 0.03), followed by the real feedback condition (mean=0.6, SEM=0.03) and the sham feedback condition (mean=0.63, SEM=0.03). However, none of these differences were statistically significant.

5.3 True heartbeat feedback did not significantly alter descriptions of emotional experience (H3)

Beyond physiological measures, we also explored how feedback influenced participants' ability to describe and reflect on their emotional experiences. The analysis revealed no significant main effect of feedback condition on emotional vocabulary, $F(2, 23) = 0.52$, $p = 0.5939$, indicating that participants did not use a significantly different number of unique emotion-related words across the true feedback (TF), sham feedback (SF), and no feedback (NF) conditions. Similarly, for emotional complexity, no significant main effect of feedback condition was observed, $F(2, 23) = 1.06$, $p = 0.3515$. Descriptive statistics revealed some variation between conditions, with

Table 2. Mixed model terms modulating the difference between emotional disturbance to amusing videos and emotional disturbance to fear videos.

Term	**Estimate**	**Std. Error**	**DFDen**	**t Ratio**	**p**	**FDR p**
Noticing	0.35	0.37	12.00	0.95	0.36	0.50
Not-Distracting	1.06	0.43	12.00	2.46	0.03	0.10
Not-Worrying	-1.29	0.44	12.00	-2.95	0.01	0.06
Attention Regulation	-1.75	0.39	12.00	-4.45	0.00	0.02
Emotional Awareness	1.41	0.45	12.00	3.14	0.01	0.05
Self-Regulation	-0.21	0.23	12.00	-0.94	0.36	0.50
Body Listening	-0.12	0.25	12.00	-0.46	0.65	0.69
Trusting	-0.31	0.24	12.00	-1.29	0.22	0.42
DERS-16_Score	0.96	0.29	12.00	3.29	0.01	0.05
Condition [Real feedback]	-0.05	0.08	12.00	-0.71	0.49	0.58
(Noticing - 3.75) × Condition	-0.31	0.19	12.00	-1.67	0.12	0.27
(Not-Distracting - 3.92) × Condition	-0.26	0.22	12.00	-1.21	0.25	0.43
(Not-Worrying - 3.80) × Condition	0.14	0.22	12.00	0.65	0.53	0.59
(Attention Regulation - 3.29) × Condition	-0.20	0.20	12.00	-1.00	0.34	0.50
(Emotional Awareness - 3.24) × Condition	0.37	0.23	12.00	1.64	0.13	0.27
(Self-Regulation - 3.39) × Condition	-0.31	0.11	12.00	-2.69	0.02	0.07
(Body Listening - 3.20) × Condition	0.01	0.13	12.00	0.06	0.95	0.95
(Trusting - 3.32) × Condition	0.22	0.12	12.00	1.85	0.09	0.24
(DERS-16_Score - 2.26) × Condition	0.12	0.15	12.00	0.85	0.41	0.53

the TF condition exhibiting slightly higher positive sentiment scores (mean = 4.07) compared to SF (mean = 3.63) and NF (mean = 2.55), as well as a marginally lower negative score in the TF condition (mean = 3.62) relative to SF (mean = 5.29) and NF (mean = 5.37). However, statistical tests did not confirm significant effects of condition on positive scores, $F(2, 23) = 1.04$, $p = 0.3591$, or negative scores, $F(2, 23) = 0.90$, $p = 0.4094$. The analysis did not reveal significant effects of feedback condition on the vocabulary, complexity, or valence of participants' open-ended responses.

To test whether individual differences mediated the effect of stimulation condition on emotional vocabulary, we performed the same mixed-effect model analysis as we used to analyze disturbance ratings, except in this case, the dependent variables analyzed were the number of emotional words, emotional complexity, and positive and negative sentiment scores. Unlike the disturbance ratings, we did not find any significant associations with MAIA self-regulation. However, we find that score on the MAIA Not-distracting scale mediated the effect of stimulation condition, such that participants who scored high on this scale expressed less negative sentiment in the true heartbeat condition compared to the sham heartbeat condition. The interaction term (Not-Distracting − 3.96) × Condition[True heartbeat Feedback] had a significant negative effect on negative sentiment scores ($F(1, 16) = 6.58$, $p = 0.021$, estimate = -3.62).

5.4 Participant Feedback and Real-world Feasibility

To evaluate real-world feasibility, we collected user experience data through both quantitative ratings and qualitative feedback. Participants rated the vibration's comfort on a 7-point Likert scale (1 = completely comfortable,

Table 3. Mixed model terms modulating the change in arousal induced by viewing fear clips.

Term	Estimate	Std. Error	DFDen	t Ratio	p	FDR p
Intercept	1.57	7.76	14.90	0.20	0.843	N/A
DERS-16_Score	0.08	0.65	15.70	0.12	0.907	0.934
Interoceptive confusion	-0.71	1.84	14.90	-0.39	0.704	0.870
Noticing	0.44	1.05	15.00	0.42	0.679	0.870
Not-Distracting	2.33	1.16	15.00	2.00	0.064	0.655
Not-Worrying	-1.19	1.05	15.10	-1.14	0.272	0.816
Attention Regulation	-0.75	1.30	14.80	-0.58	0.572	0.858
Emotional Awareness	0.08	0.94	15.70	0.08	0.934	0.934
Self-Regulation	-0.66	0.65	15.40	-1.01	0.327	0.858
Body Listening	0.10	0.69	14.80	0.14	0.887	0.934
Trusting	0.29	0.63	14.90	0.46	0.651	0.870
Condition [Real feedback]	-0.27	0.30	14.90	-0.89	0.389	0.858
(DERS-16_Score - 2.33) × Condition	0.40	0.51	15.40	0.78	0.449	0.858
(Interoceptive confusion - 2.96) × Condition	0.86	1.42	14.60	0.61	0.554	0.858
(Noticing - 3.75) × Condition	-1.29	0.81	14.70	-1.59	0.133	0.655
(Not-Distracting - 4.00) × Condition	-1.18	0.90	14.70	-1.31	0.211	0.738
(Not-Worrying - 3.92) × Condition	1.21	0.81	14.80	1.50	0.156	0.655
(Attention Regulation - 3.36) × Condition	0.09	1.00	14.60	0.09	0.928	0.934
(Emotional Awareness - 3.31) × Condition	0.51	0.74	15.40	0.69	0.502	0.858
(Self-Regulation - 3.49) × Condition	-1.55	0.51	15.10	-3.06	0.008	0.168
(Body Listening - 3.25) × Condition	0.94	0.53	14.60	1.76	0.099	0.655
(Trusting - 3.29) × Condition	0.31	0.48	14.60	0.64	0.530	0.858

7 = very uncomfortable), yielding a low average discomfort score (M = 2.68, SEM = 0.31), suggesting general comfort with wearing the device throughout the experiment.

Several participants described the vibrations as helpful for increasing awareness of their bodies, particularly during intense scenes. One participant noted, "It made me a bit more conscious of my heart." Many participants ($N = 6$) found the vibrations helpful for regulating their emotions: *"It reminded me to breathe and calm myself; it definitely increased my awareness of emotions, especially during the horror movies."* Others ($N = 10$) described the feedback as grounding or emotionally supportive (P1: *"...made me a bit conscious of my heart the whole time; felt like it grounded me."*; P2: *"...made me focus more on how my body was reacting to the movie."*). The majority ($N = 8$) reported that the vibrations were surprisingly unobtrusive (P5: *"I was aware of it, but it didn't bother me."*; P7: *"No, it was barely noticeable."*), whereas a few ($N = 3$) experienced mild discomfort or distraction during the early blocks (P4: *"...mildly irritating... I felt more in control without them in the second round."*). These findings suggest that haptic feedback delivered through a smartwatch can be a feasible approach for in situ emotion regulation. However, future systems should account for individual variability, emotional context, and potential adaptation over time to optimize effectiveness.

6 DISCUSSION

6.1 Empirical Insights

Trait-dependent Effects. This study explored the impact of heartbeat-synchronized feedback from a smartwatch on emotional experience during amusement- and fear-inducing video clips. While we did not observe a main

Table 4. Mixed model terms modulating the change in valence induced by viewing fear clips.

Term	Estimate	Std. Error	DFDen	t Ratio	p	FDR p
DERS-16_Score	-0.20	0.47	15.50	-0.43	0.670	0.83
Interoceptive confusion	-2.35	1.34	15.00	-1.75	0.101	0.52
Noticing	-0.83	0.76	15.00	-1.08	0.297	0.52
Not-Distracting	-1.06	0.85	15.00	-1.25	0.230	0.52
Not-Worrying	1.01	0.76	15.10	1.33	0.203	0.52
Attention Regulation	-1.41	0.95	14.90	-1.49	0.158	0.52
Emotional Awareness	0.29	0.68	15.50	0.43	0.670	0.83
Self-Regulation	-0.53	0.47	15.30	-1.13	0.277	0.52
Body Listening	0.86	0.50	14.90	1.71	0.109	0.52
Trusting	-0.46	0.46	14.90	-1.01	0.331	0.53
Condition [Real feedback]	0.11	0.13	14.40	0.81	0.433	0.63
(DERS-16_Score - 2.33) × Condition	-0.30	0.23	14.80	-1.34	0.199	0.52
(Interoceptive confusion - 2.96) × Condition	-0.81	0.63	14.30	-1.30	0.215	0.52
(Noticing - 3.75) × Condition	0.39	0.36	14.40	1.08	0.299	0.52
(Not-Distracting - 4.00) × Condition	0.11	0.40	14.40	0.27	0.790	0.87
(Not-Worrying - 3.92) × Condition	0.11	0.36	14.40	0.29	0.772	0.87
(Attention Regulation - 3.36) × Condition	-0.59	0.44	14.30	-1.35	0.199	0.52
(Emotional Awareness - 3.31) × Condition	-0.40	0.33	14.80	-1.21	0.245	0.52
(Self-Regulation - 3.49) × Condition	-0.01	0.22	14.60	-0.05	0.958	0.96
(Body Listening - 3.25) × Condition	-0.02	0.23	14.30	-0.09	0.933	0.96
(Trusting - 3.29) × Condition	0.17	0.21	14.30	0.78	0.448	0.63

effect of feedback on emotional regulation, nor significant effects in the exploratory analyses after multiple comparisons correction, we did observe a trend suggesting that the effects of interoceptive feedback may be moderated by participants' psychological traits.

Most notably, the interaction between interoceptive feedback and trait self-regulation points toward an implicit emotion regulation mechanism: participants with higher self-regulation scores, as measured by the MAIA, benefited more from real-time heartbeat feedback. This subscale comprises four items assessing an individual's ability to reduce mental distress by attending to bodily sensations. Such individual differences appear to be a critical boundary condition for interoceptive interventions: *simply amplifying physiological signals may not support emotion regulation unless individuals already possess the implicit ability to leverage such signals.* This aligns with emerging HCI perspectives that shift from general emotion regulation to more tailored, trait-sensitive support systems [30, 51]. Rather than aiming for universal effects, our findings suggest that wearable interventions could benefit from personalization grounded in baseline interoceptive and regulatory capacities.

Emotion-specific Modulation. Interoceptive feedback also modulated the response to fear more strongly than to amusement (Table 2), consistent with the model proposing that interoception primarily improves mental health by facilitating identification and regulation of contextually inappropriate responses. However, further research is needed to fully confirm this model; for example, our results are also consistent with a model where interoceptive feedback selectively attenuates fear even when participants do not engage emotional regulation. Future studies using tasks like contextual fear conditioning with aversive stimuli and extinction learning would allow the role of interoceptive feedback to be more precisely determined.

Importantly, although our main hypotheses were not supported at the group level, our results offer valuable clarification about when and for whom interoceptive biofeedback may be effective. This refinement aligns with current efforts in HCI to define the design space for emotion regulation technologies [45, 50] by surfacing the contexts and traits that shape their success or limitations. Taken together, these findings advance a more nuanced understanding of how interoceptive feedback operates and under what conditions it is most beneficial. Our results further contribute to a deeper understanding of the role of heartbeat perception in emotional processing. If replicated, these findings suggest that amplifying interoceptive information does not automatically influence emotional experience; rather, such effects may emerge primarily among individuals already adept at using bodily signals for self-regulation. This observation could also help explain inconsistencies in prior research linking heartbeat perception to mental health outcomes [15].

Arousal versus Valence. Results suggest a nuanced role for heart rate feedback. While we observed trends that true heartbeat feedback modulated arousal, it did not significantly affect valence, nor the complexity, verbosity, or sentiment of participants' emotional descriptions. This pattern may indicate that heart rate feedback primarily modulates the intensity of emotional arousal, without altering the emotional label or category.

Measurement Considerations. A notable finding is the absence of significant effects on the heartbeat counting task, despite finding effects on emotional disturbance. While widely used, heartbeat counting is subject to several sources of noise and bias [13], which may have limited its sensitivity in this context. Furthermore, the brief 30-second intervals used in our task or the limited accuracy of the Fitbit heart rate sensor may have constrained participants' ability to perceive their heartbeats with accuracy.

6.2 Design Implications for Interoceptive Technologies

The observation that interoceptive feedback was only effective among participants with higher self-regulation scores challenges overly optimistic assumptions about the universal or standalone effectiveness of wearable biofeedback. It clarifies that real-time interoceptive signals alone may not be sufficient to induce meaningful emotional regulation without accompanying conscious attention to bodily sensations. These insights support the integration of physiological feedback with skill-building approaches such as mindfulness training, affect labeling, or guided reflection—particularly when tailored to users' interoceptive capacities and regulatory readiness. This aligns with Slovak et al.'s framework for emotion regulation interventions in HCI [50], which emphasizes supporting early-stage regulatory processes (e.g., emotional awareness) rather than assuming fully developed or deliberate control.

Moreover, this study demonstrates the feasibility of delivering interoceptive feedback through widely available consumer wearables. Translating cardiac signals into subtle, wrist-based vibrations offers notable advantages: it does not require additional hardware, remains unobtrusive, and can be used in everyday settings. Preliminary user experience data suggest that the device was generally well-received, with participants describing the vibrations as grounding, calming, or helpful for emotional awareness—particularly during high-arousal or fear-evoking stimuli. Unlike many interoceptive training methods that demand extensive practice, our findings suggest that real-time smartwatch feedback can produce immediate modulation of emotional disturbance—at least among individuals with high interoceptive self-regulation. This makes the approach particularly promising as a scalable and accessible tool for augmenting in-the-moment mental health support.

Taken together, these design-relevant insights reinforce that biofeedback systems should be adaptive not only to users' momentary physiological states but also to their individual capacities for interpreting and acting upon interoceptive cues. Future systems may therefore benefit from initial assessments of interoceptive traits and dynamically tailored feedback strategies aligned with user profiles.

7 LIMITATIONS AND FUTURE WORK

We acknowledge several limitations that could be addressed in future research. First, our study employed an exploratory statistical approach to identify individual differences in response to interoceptive feedback. While the findings are promising, the observed interaction between heart rate feedback and self-regulation ability did not remain significant after correction for multiple comparisons and thus requires replication in a larger, confirmatory study.

Because the study was conducted in a single-session laboratory setting, we were unable to examine longer-term or real-world effects. To build upon the initial evidence from this study, we are planning an in-the-wild investigation to examine how sustained exposure to feedback unfolds over time and across everyday contexts. Such a study could clarify whether users develop greater fluency with bodily signals and improve their ability to leverage interoceptive cues for self-regulation beyond controlled environments.

Additionally, the feedback benefited only participants with high trait self-regulation, suggesting that wearable interoceptive systems may not be universally effective. Pairing these technologies with prior training in interoceptive awareness—such as mindfulness-based interventions [23]—may enhance their effectiveness, particularly for users with lower interoceptive capacity. Future studies should consider including baseline assessments of interoceptive sensitivity or incorporating skill-development interventions that help users interpret subtle physiological cues and achieve more effective emotion regulation.

The use of horror films effectively elicited emotional responses, yet some participants reported finding them more enjoyable than distressing, which may have influenced their engagement. Including a broader range of emotional stimuli—including neutral or low-arousal clips—could help account for variability in emotional responses. Moreover, film-based stimuli may not fully replicate the physiological and emotional intensity of real-world high-stakes scenarios, such as social conflict, trauma exposure, or performance pressure. Future work should explore the ecological validity of feedback effects in diverse, emotionally charged contexts.

Despite counterbalancing, potential carryover effects between feedback conditions remain a concern. Longer washout periods, session randomization, or a design between-subjects may improve experimental control. The study also relied on a single haptic feedback modality, which, although practical, may not suit all users. Exploring multimodal feedback (e.g., combining vibration with visual or auditory cues) could increase inclusivity by accommodating diverse sensory preferences.

Finally, feasibility data suggest that smartwatch-based feedback was generally acceptable and non-intrusive. However, further work is needed to evaluate long-term usability in daily life settings, such as whether continuous feedback becomes distracting, fatiguing, or socially awkward in workspaces or public settings. Evaluating user preferences, comfort, and privacy concerns across diverse populations will be key to determining the translational viability of such interventions.

8 CONCLUSION

In this study, we investigated the potential of real-time, heartbeat-synchronized haptic feedback to enhance interoceptive accuracy and emotion regulation during emotionally evocative experiences. Participants experienced three feedback conditions—True Feedback, Sham Feedback, and No Feedback—while viewing fear- and amusement-inducing video clips. Measures included interoceptive accuracy, emotional disturbance, and individual differences in interoceptive ability and self-regulation, as assessed by the MAIA-2.

Although the feedback condition did not yield significant main effects across the entire sample or effects significant after multiple comparisons correction, exploratory analyses revealed a promising trend: participants who reported using interoception for self-regulation exhibited stronger modulation of emotional responses—specifically to fear-inducing clips—when receiving true heartbeat feedback. Notably, this modulation appeared specific to the arousal dimension of emotion, with no consistent effects observed on valence or verbal emotional expression.

While prior work has examined the influence of false heart rate feedback on emotion and cognition [9, 10], our study is, to our knowledge, the first to assess whether enhancing perception of one's true heartbeat can support implicit emotion regulation. While both approaches can be seen to rely on similar hardware, they likely involve distinct underlying mechanisms: false feedback may shape emotion through expectancy-driven modulation, whereas true heartbeat feedback appears to reinforce bottom-up interoceptive awareness, potentially supporting self-regulatory processes in individuals already attuned to internal bodily signals.

These findings suggest that real-time interoceptive feedback holds promise as a mechanism for supporting emotional regulation, particularly when tailored to an individual's interoceptive tendencies and self-regulatory capacity. By identifying when and for whom such feedback is most effective, this work advances the understanding of interoceptive technologies and informs the design of future wearable systems aimed at enhancing emotional self-awareness.

More broadly, our findings surface boundary conditions under which interoceptive feedback may be beneficial in emotionally charged contexts. We present this work as an exploratory step toward designing emotionally adaptive technologies and mental health interventions that account for individual differences in bodily awareness and regulatory style. As interoceptive wearables continue to advance, future research can build on this foundation to create more personalized and effective tools for fostering emotional resilience and well-being.

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