Temporal and Multisensory Integration of Cardiac and Auditory Signals: Implications on Interoception, Cardiac Function, and Emotion

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Universidade do Minho
Escola de Psicologia

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Professora Doutora Adriana Sampaio

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Universidade do Minho, 29 de janeiro de 2024

Assinado por: **Ricardo José Pereira da Silva**
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(Ricardo José Pereira da Silva)

Integração Temporal e Multissensorial de Sinais Cardíacos e Auditivos: Implicações na Interoceção, Função Cardíaca, e Emoção

Resumo

A capacidade de integrar informação sensorial do ambiente (exteroceção) e de estados fisiológicos internos (interoceção) – integração intero-exterocetiva – é um aspeto fundamental da nossa consciência, resultando numa representação multissensorial do nosso corpo no mundo. Ao coordenar a sua atividade neural às dinâmicas intero-exterocetivas, o cérebro produz respostas temporais adaptativas à sua complexidade através de sincronização temporal, modulando as dinâmicas fisiológicas, emocionais, e cognitivas das nossas esferas individuais e sociais. Deste modo, anomalias nestes processos podem resultar em incerteza em relação a estados corporais e estados emocionais e cognições mal adaptativas. Intervenções recentes baseadas em biofeedback cardíaco, mindfulness, e audição musical têm demonstrado resultados promissores neste aspeto. O objetivo deste estudo foi desenvolver um sistema musical interativo baseado em biofeedback cardíaco e observar o seu efeito em aspetos de interoceção, função cardíaca, e estados emocionais subjetivos, bem como explorar diferenças individuais em interoceção (autorrelato), psicopatologia, e representação emocional. Uma amostra de 24 participantes saudáveis foi dividida em três grupos, cada um efetuando uma sessão de uma tarefa de atenção: 1) atenção cardíaca mindful (interocetiva), 2) audição musical não-interativa (exterocetiva), e 3) audição musical interativa (intero-exterocetiva). Foram avaliadas medidas de interoceção (comportamentais e de autorrelato), função cardíaca, estados emocionais subjetivos, psicopatologia e representação emocional. Encontrámos diferenças significativas em precisão interocetiva no grupo intero-exterocetivo, bem como melhorias em função cardíaca e redução de afeto negativo em todos os grupos. Também confirmámos o papel preditivo de aspetos de psicopatologia, e habilidades interocetivas e de representação emocional. Em suma, estes resultados demonstraram a eficácia do sistema musical interativo na otimização de interoceção, função cardíaca, e estados emocionais, sugerindo que esta abordagem poderá facilitar processos de integração intero-exterocetiva e sincronização temporal, melhorando níveis de certeza acerca de estados corporais, e convidando atenção plena e estados emocionais e fisiológicos calmos.

Palavras-chave: Emoção, Função Cardíaca, Integração Multissensorial, Interoceção, Sincronização Temporal

Temporal and Multisensory Integration of Cardiac and Auditory Signals: Implications on Interoception, Cardiac Function, and Emotion

Abstract

The ability to integrate sensory information from the environment (exteroception) and internal physiological states (interoception) – intero-exteroceptive integration – is a key aspect of our consciousness, resulting in a multisensory representation of our body in the world. By coordinating its neural activity to intero-exteroceptive dynamics, the brain produces temporal-based responses to adapt to their complexity through temporal synchronization, modulating the physiological, emotional, and cognitive dynamics of our individual and social spheres of experience. Abnormalities in these processes may thus result in uncertainty about bodily states and maladaptive emotional states and cognitions. Recent interventions employing cardiac biofeedback, mindfulness, and music listening have shown promising results in this respect. The aim of this study was to develop a cardiac biofeedback-based interactive music system and observe its effect on interoception, cardiac function, and subjective emotional states. We also aimed to explore individual differences in self-reported interoception, psychopathology, and emotion representation. A sample of 24 healthy participants was divided into three groups, each performing a single-session attention task: 1) heartbeat mindful attention (interoceptive), 2) non-interactive music listening (exteroceptive), and 3) interactive music listening (intero-exteroceptive). Measures of self-report and task-based interoception, cardiac function, subjective emotional states, psychopathology, and emotion representation were assessed. Significant differences were found in interoceptive accuracy in the intero-exteroceptive group, as well as improvements in cardiac function and reduction of negative affect in all groups. We also confirmed the predictive role of psychopathology, and interoceptive and emotion representation abilities. Together, these results demonstrated the effectiveness of interactive music systems in improving aspects of interoception, cardiac function, and subjective emotional states, suggesting that this approach may facilitate intero-exteroceptive integration and temporal synchronization, enhancing one's certainty about bodily states, while inviting mindful attention and calm emotional and physiological states.

Keywords: Cardiac Function, Emotion, Interoception, Multisensory Integration, Temporal Synchronization

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1. INTRODUCTION

Our consciousness and everyday experience are significantly determined by the relationship between the body and the environment, with the brain acting as its mediator and coordinator (Northoff et al., 2023; Northoff, 2016). As we receive and integrate internal and external streams of sensory signals, a multisensory representation of our body in the world emerges, along with a sense of *self* and body ownership (Seth, 2021; Suzuki et al., 2013; Tsakiris, 2017), as well as the emotional and social representations that we carry into our *self-other* relations (Tsakiris, 2017; Palmer & Tsakiris, 2018; Payne-Allen & Pfeifer, 2022).

The sensory modalities that connect us to the outside world are collectively known as *exteroception*, involving our external senses of sight, hearing, taste, touch, and smell, which are further integrated with vestibular, proprioceptive, and voluntary motor systems (Valenzuela-Moguillansky, et al., 2017; Seth, 2021). On the other hand, the perceptual and sensory modalities associated with our awareness and representation of our body's internal states are known as *interoception*, and correspond to the process of sensing, interpreting, integrating, and regulating visceral signals by our nervous system (Khalsa et al., 2018; Chen et al., 2021). It is the multisensory integration of interoception and exteroception or, in other words, the *intero-exteroceptive balance*, which underlies the relationship between body and environment in our awareness (Northoff, 2016).

The last decade has seen a rising interest in the study of the multisensory integration of interoceptive and exteroceptive dimensions, namely in the study of the *self* (Tsakiris, 2017; Seth, 2013, 2021), body-ownership (Suzuki et al., 2013; Valenzuela-Moguillansky, et al., 2017; Tsakiris, 2017), emotion (Seth, 2013, 2021), and the *self-other* relationship (Tsakiris, 2017; Palmer & Tsakiris, 2018; Noel et al., 2018; Payne-Allen & Pfeifer, 2022). The interoceptive dimension has gained significant emphasis, given its implications not only on several psychophysiological (e.g., homeostasis) and cognitive functions (e.g., attention, decision-making, emotional regulation), but also on the impact of its dysfunction in various psychiatric disorders (e.g., anxiety and mood disorders, eating disorders), which reinforces the need to establish sound methods for its study, assessment and intervention (Khalsa et al., 2018; Chen et al., 2021).

1.1. Multisensory Integration & Temporal Synchronization

The neural underpinnings of interoception rely on the *interoceptive nervous system* (INS; Carvalho & Damásio, 2021; Damásio, 2021), which is responsible for sensing and monitoring physiological changes (e.g., chemical, oscillatory, anatomical), creating a moment-to-moment mapping of the homeostatic state of one's body, as well as orchestrating regulatory responses (Khalsa et al., 2018; Chen et al., 2021; Carvalho & Damásio, 2021; Petzschner et al., 2021; Damásio, 2021). This system is particularly unique in comparison to exteroceptive systems (e.g., vision), as it possesses an interactive arrangement between the object (i.e., the body) and the subject (i.e., generated by the central nervous system; CNS) of perception (Carvalho & Damásio, 2021). This means that the afferent (i.e., bottom-up) signals being monitored and perceived by the CNS can be regulated and modified directly by the CNS via efferent (i.e., top-down) commands, at multiple levels of the INS, both central and peripheral (Carvalho & Damásio, 2021; Damásio, 2021; Chen et al., 2021; Petzschner et al., 2021). The structure of the INS involves a complex interaction between interoceptive signals originating from visceral and body structures (e.g., heartbeats, blood pressure), their neural translation and signaling through autonomic afferent and efferent pathways (e.g., vagal, and spinal), and their processing, integration, and regulation within subcortical and cortical structures of the CNS (Khalsa et al., 2018; Chen et al., 2021; Petzschner et al., 2021).

The insular cortex plays a key role within the INS not only in interoception but also in multisensory integration, as it receives and integrates inputs from both interoceptive and exteroceptive sources, while connecting various other functional large-scale systems involved in emotion, motivation, cognition, and social connection (Gogolla, 2017; Palmer & Tsakiris, 2018). These connective and integrative properties of the insula allow, simultaneously: 1) the monitoring and continuous representation of one's external environment (i.e., exteroception) and inner bodily states (i.e., interoception) (Gogolla, 2017), thus reflecting the *intero-exteroceptive balance* that underlies the body-environment relationship in our awareness (Northoff, 2016); 2) while its integration within important circuits of the CNS such as the salience network (responsible for assigning salience to stimuli and their emotional correlates), the somatomotor network (involved in body awareness), and the default mode network (underlying our sense of *self*), reflects how we integrate and allocate attention and awareness to intero- and exteroceptive dimensions, while being grounded in one's body and *self* (Tumati et al., 2021; Gogolla, 2017; Northoff, 2016).

Of note, both neural and visceral activity are essentially rhythmic (i.e., oscillatory) and variable (Khalsa et al., 2018; Petzschner et al., 2021). As visceral signals are conveyed to the brain via the multilevel hierarchy of the INS, their rhythmic properties interact, resulting in dynamic temporal-based responses in neural activity (e.g., phase-locking, phase-shifting), which can be defined as entrainment (Lakatos et al., 2019), or synchronization (Tumati et al., 2021). From a multisensory integration and temporo-spatial perspective (Northoff et al., 2023; Northoff & Huang, 2017), temporal synchronization is a process by which "the brain adapts and coordinates its neuronal activity's dynamics to interoceptive bodily and exteroceptive environmental dynamics" (Northoff et al., 2023, p. 2). This view can be further expanded by predictive coding and interoceptive inference (Seth & Friston, 2016; Seth, 2013, 2021), suggesting that the degree of temporal synchronization influences the degree of prediction errors (i.e., mismatch between expected and actual sensory signals) and, subsequently, the attentional dynamics and allostatic load (i.e., degree of regulatory actions aimed at homeostatic stability) needed to perceive and resolve them (Tumati et al., 2021).

Temporal synchronization also occurs at the level of cardiac function (i.e., neuro-cardiac synchronization), since heartbeats are continuous rhythmic internal stimuli that have been shown to entrain neural activity in several regions of the CNS responsible for attention (Petzchner et al., 2019), time perception (Arslanova et al., 2023), emotion (Garfinkel et al., 2014), interoceptive awareness (Petzchner et al., 2019), body-ownership (Park et al., 2016), and sense of *self* (Babo-Rebelo et al., 2021), as measured by heartbeat-evoked potentials (HEP; i.e., event-related potentials in the brain indexing increased amplitude of neural activity that is time-locked to R-peaks in cardiac activity; Park & Blanke, 2019). Furthermore, studies using intero-exteroceptive synchronization paradigms (e.g., cardiac-visual) have shown that, when presented with visual stimuli synchronized with one's heartbeat, participants reported stronger sense of body-ownership (Suzuki et al., 2013; Aspell et al., 2013), corresponding in turn to a stable sense of *self*, grounded in one's interoceptive abilities (Palmer & Tsakiris, 2018).

Together, these findings highlight the importance of intero-exteroceptive integration and temporal synchronization not only in maintaining a stable sense of *self* and body-ownership, but also in regulating homeostatic, attentional, and emotional dynamics which pervade our individual and social spheres of experience.

1.2. Cardiac Interoception, Emotion & Social Connection

The process of interoceptive inference, through its matching of ascending interoceptive signals and descending predictions stemming from internal models or representations of one's body state, results in subjective perceptual contents, which are manifested in emotional experiences and moods (Seth, 2013, 2021). This suggests that not only is emotional experience modulated by interoceptive processes, but it is in fact constituted by them through interoceptive inference, grounded in intero-exteroceptive integration across the multiple levels of the INS (Seth, 2013, 2021; Carvalho & Damásio, 2021), which overlap with various structures responsible for emotional processing and regulation (Critchley & Garfinkel, 2017; Seth, 2013). Abnormal interoceptive inference and intero-exteroceptive integration can therefore lead to misinterpretation of emotional states and experiences, and maladaptive emotion regulation (Tumati et al., 2021).

Improvements in interoceptive inference (i.e., reduction of prediction errors between expected and actual sensory signals) and intero-exteroceptive integration, in this sense, are key to accurately represent and regulate one's bodily and emotional state, as well as to associate those representations to one's body (i.e., body-ownership) and sense of *self*, thus preserving the latter's stability (Seth, 2013, 2021). This is especially relevant to social connection (e.g., emotion recognition and representation, empathy), since having stable and accurate representations of one's own emotional state and *self* is essential to understanding how other's emotional states affect us (Arnold et al., 2019; Palmer & Tsakiris, 2018), as well as maintaining a stable degree of *self-other* distinction (i.e., ability to distinguish one's own actions, perceptions, and emotions, from those of others; Lamm et al., 2016), and an adaptable degree of *self-other* overlap (i.e., tendency for an observer to engage in the same emotional state as the person observed; Preston & Hofelich, 2012; Palmer & Tsakiris, 2018). As with interoceptive inference (Seth, 2013, 2021), effectively understanding others' emotional states implies having inner models that can dynamically represent the spectrum of other's emotional states (Keating et al., 2023).

Arnold and colleagues (2019) have proposed that interoception facilitates social connection through the degree of flexibility in intero-exteroceptive attention allocation (i.e., between inner emotional states and outer social dynamics), which reflects the importance of assessing attention styles in this respect (Mehling, 2016). Maladaptive attentional styles (e.g., hypervigilance towards negative exteroceptive and interoceptive stimuli) could thus be at the basis of emotional and social dysregulations in, for instance, depression or anxiety disorders (Arnold et al., 2019; Tumati et al., 2021). Additionally, the authors further propose that better interoceptive ability and awareness translate into richer emotional experiences, which in turn facilitate the empathic understanding and response to other's emotions, thus improving social connection (Arnold et al., 2019). These propositions highlight the importance of establishing sound methods of study, assessment, and intervention for the improvement of interoceptive abilities and awareness in both clinical and non-clinical populations (Khalsa et al., 2018; Chen et al., 2021).

The study of interoception is inherently challenging, considering the difficulty in measuring and manipulating interoceptive signals accurately and non-invasively and in understanding their dynamics within the nervous system (Tsakiris, 2017; Seth 2021). Notwithstanding, interoceptive science has adopted different taxonomies and approaches for the assessment of interoceptive processes and abilities, using self-report questionnaires, experimental tasks, and neurophysiological correlates (Khalsa et al., 2018). The main discriminable features of interoceptive ability are *interoceptive accuracy, interoceptive sensibility,* and *interoceptive awareness* (Khalsa et al., 2018; Mehling, 2016; Garfinkel et al., 2015).

Interoceptive accuracy (IAcc) is understood as one's objective performance in interoceptive behavioral tasks (Khalsa et al., 2018; Garfinkel et al., 2015, 2016). Cardiac discrimination tasks (Katkin et al., 1983) are widely used in this context, focusing on the ability to determine whether external auditory cues are synchronized with one's own heartbeats, thus reflecting intero-exteroceptive integration (Garfinkel et al., 2015). Interoceptive sensibility (IS) corresponds to self-reported interoception, relating to both one's belief in their interoceptive ability (e.g., task-related confidence ratings) and the degree of subjective engagement with interoceptive signals (e.g., self-report questionnaires; Garfinkel et al., 2015; Mehling, 2016). One advantage of self-report questionnaires is the ability to distinguish between *anxiety-driven* (e.g., somatization, hypervigilance, anxiety) and *mindful* (i.e., healthy, adaptative, resilient) *attention styles* towards interoceptive signals (Mehling, 2016).

Finally, interoceptive awareness (IAw) is broadly defined as the ability to consciously experience and report interoceptive features (Khalsa et al., 2018; Mehling, 2016; Garfinkel et al., 2015). One common measure is *metacognitive awareness* of interoceptive ability, quantified as the correspondence between confidence ratings and objective performance in interoceptive tasks, thus reflecting a relationship between subjective and objective interoceptive ability (Garfinkel et al., 2015). However, this definition has been contested (Mehling, 2016), urging the need to broaden the scope of IAw through a multidimensional approach, combining task-based and self-report measures based on attentional and regulatory styles (Mehling, 2016), as well as neurophysiological insights (Khalsa et al., 2018; Carvalho & Damásio, 2021).

1.3. Cardiac Interoception, Biofeedback & Interactive Music Systems

One promising approach to the improvement of interoception is the use of cardiac biofeedback training (Meyerholtz et al., 2019), which consists in receiving exteroceptive feedback (e.g., visual, auditory, tactile) on one's cardiac activity and, through this process, learn to accurately perceive and modulate it (Meyerholtz et al., 2019). Various approaches in cardiac biofeedback training also employ resonance breathing to improve cardiovascular mechanisms, such as heart rate variability (HRV), i.e., variations in the time-intervals between adjacent heartbeats (Leganes-Fonteneau et al., 2021; Schumann et al., 2021; Lehrer et al., 2020; Shaffer et al., 2014).

HRV is an important marker of health, adaptability, and resilience of various regulatory systems (i.e., physiological, cognitive, emotional) (Schaffer et al., 2014; Pinna & Edwards, 2020), reflecting neuro-cardiac synchronization along the multilevel hierarchy of the INS, especially the influence of vagus nerve activity (Pinna & Edwards, 2020; Laborde et al., 2017; Shaffer et al., 2014). Modulation of HRV via resonance breathing has also been suggested to improve interoceptive awareness by reducing interoceptive prediction errors, thus facilitating interoceptive inference (Leganes-Fonteneau et al., 2021).

Other methods of improving aspects of interoception involve training based on heartbeat perception tasks (Schillings et al., 2022), mindfulness-based body awareness (Fischer et al., 2017; Price & Hooven, 2018), and listening to heartbeat sounds (Lenggenhager et al., 2013), which has been found to significantly activate areas of the INS (Kleint et al., 2015). Music listening has also been demonstrated as a promising approach, given its unique influence on homeostatic states and allostatic regulation (i.e., self-regulating one's homeostatic state by adaptative music listening), and on emotional (e.g., arousal) processes (Reybrouck et al., 2021; Krause et al., 2023), as well as its potential for intero-exteroceptive entrainment (Lakatos et al., 2019; Northoff, 2016).

Inspired by biofeedback techniques, interactive music systems translate one's interoceptive signals (e.g., cardiac) into ambient musical feedback via generative musical algorithms, whose elements are temporally synchronized to and dynamically modulated by one's homeostatic state and allostatic activity, while at the same time encouraging mindful attention and inviting calm emotional and physiological states (Leslie et al., 2019; Yu et al., 2018). Ambient music, in this context, "is intended to induce calm and a space to think" and "must be able to accommodate many levels of listening attention without enforcing one in particular; it must be as ignorable as it is interesting" (Eno, 1978).

1.4. Study Aims & Hypotheses

Considering the role of intero-exteroceptive integration, and its relationship with allostatic regulation, emotional states and experiences, and social connection, the main objective of this study was to investigate the effects of an interactive music system on interoception, cardiac function, and subjective emotional states. We also intended to understand how these effects relate to individual differences in subjective aspects of interoceptive awareness (e.g., attentional and regulatory styles), depression, anxiety, and stress-related symptomology, and to the subject's representations of other's emotional expressions.

With this aim in mind, as a preliminary goal, an interactive music system was developed and employed in a single session intervention, as a proof-of-concept. This intervention involved an intero-exteroceptive attentional task applied to three experimental conditions or groups that reflect the different dimensions of intero-exteroceptive integration: biofeedback-based interactive music listening (intero-exteroceptive), non-interactive music listening (exteroceptive) and heartbeat mindful attention (interoceptive). Subsequently, we aimed to: 1) explore the effect of the intervention across time (T1 and T2), and between groups, namely in regards to task-based interoception (IAcc, IS, and IAw), cardiac function (HR and HRV) and emotional correlates (e.g., negative and positive affect); and 2) to explore individual differences of self-reported interoception, psychopathology (depression, anxiety and stress), and emotion representation, both in general and, more specifically, on the effects of the intervention.

We hypothesized that: 1) the intero-exteroceptive group would demonstrate improvements in interoceptive awareness (mainly IAcc) and cardiac function (i.e. decreased heart rate and increased HRV), as well as in the valence of subjective emotional states, when compared to the other groups; 2) dimensions of self-reported interoception, psychopathology, and emotion representation, would play a moderating role on the effects of the intervention; and 3) task-based and self-reported interoception, cardiac function, emotion representation and psychopathology would be significantly associated among themselves in terms of individual differences.

2. METHODS

2.1. Participants

A power analysis was employed using G*Power v3.1.9.7, considering an 80% power to determine a medium effect size at 0.2 (Cohen's *f*), at an alpha level of 0.05. This analysis resulted in an estimated total sample size of 244 participants, adequate for a comprehensive randomized controlled trial. However, recommendations for sample size calculation for proof-of-concept evaluations or external pilot trials (i.e., a pilot trial run before the main comprehensive study) were followed (i.e., at least 9% of the estimated sample for the comprehensive trial; Cocks & Torgerson, 2013). The final power analysis resulted in a sample of 21 participants, distributed equally between the 3 experimental groups: group 1 (interoceptive; n = 7), group 2 (exteroceptive; n = 7), and group 3 (intero-exteroceptive; n = 7).

Our sample comprised 24 healthy participants aged between 18 and 40 years old (M_{age} = 23.75, *SD* = 5.4). Twenty-one (87.5%) were female participants (M_{age} = 22.76, *SD* = 1.00), and three (12.5%) were male participants (M_{age} = 30.67, *SD* = 3.8). All participants were Portuguese and most had an education level greater than secondary education (*n* = 15; 62.5%).

The inclusion criterion was age (18-40 years old), while exclusion criteria included presence of cardiorespiratory disease, diagnosed anxiety or other psychiatric disorders, and allergic reactions to textiles, namely, polyester (as per the cardiac sensor's safety recommendations). Age requirements were based on findings on the effectiveness of cardiorespiratory biofeedback interventions on adults older than 40 (Leganes-Fonteneau et al., 2021) and on age-related decline (in middle aged adults, 40 to 60) in interoceptive awareness (Khalsa et al., 2009). Most participants were university students recruited from the SONA credit platform of the University of Minho, receiving 5 credits for full participation in this study.

Participants were first screened to assess their eligibility and were then contacted via e-mail with information (e.g., instructions, links, and scheduling information) about the different phases of the study: 1) assessment via online self—report questionnaires (Qualtrics, Provo, UT; Version 2023); 2) an online emotion representation task (Gorilla platform); and 3) an in-person experimental session. At each phase of the study, participants provided signed informed consent.

2.2. Instruments

Screening & Demographic Questionnaire

In an initial recruitment questionnaire, demographic data included age, gender, nationality, and educational level (in years), followed by questions regarding participant's eligibility: absence of cardiorespiratory diseases, diagnosed anxiety or other psychiatric disorders, or allergic reactions to polyester.

Multidimensional Assessment of Interoceptive Awareness (MAIA)

Participants completed the Portuguese version (Machorrinho et al., 2019) of the MAIA (Mehling et al., 2012), composed of 33 self-report items measuring 7 scales of interoceptive awareness. Each item consists of a statement which participants must rate, using a 6-point Likert scale (0 – never; 5 – always), how often does it apply to them in their daily life. Higher scores on each scale reflect more positive aspects of interoceptive awareness.

The MAIA contains 7 dimensions of interoceptive awareness, namely (with internal consistency levels [α] reported for this study): Noticing (awareness of uncomfortable, pleasant, and neutral body sensations; α = .51), Not-Distracting (tendency to not self-distract to cope with body sensations of pain and discomfort; α = .81), Not-Worrying (ability to maintain emotional balance with sensations of pain and discomfort; α = .67), Attention Regulation (ability to sustain and control attention to body sensations; α = .63), Emotional Awareness (awareness of the relation between body sensations and emotional states; α = .72), Self-Regulation (ability to regulate distress by paying attention to body sensations; α = .88), and Trusting (ability to experience one's body as safe and trustworthy; α = .80) (Machorrinho et al., 2019; Mehling et al., 2012).

Body Perception Questionnaire (BPQ)

The Body Awareness section of the Portuguese adaptation (Campos et al., 2021) of the BPQ (Porges, 1993) was used, showing an internal consistency level of α = .96. This section contains 26 self-report items referring to bodily sensations, scored with a 5-point Likert scale (1 – never; 5 – always). For each item, participants must rate how frequently they are aware of specific bodily sensations in their daily life. This questionnaire measures one's sensitivity to interoceptive inputs, with higher values reflecting hypersensitivity, while lower values reflect hyposensitivity (Kolacz et al., 2018; Garfinkel et al., 2015).

Depression, Anxiety, and Stress Scale (DASS-21)

The Portuguese version (Pais-Ribeiro et al., 2004) of the DASS-21 (Lovibond & Lovibond, 1995), was administered to assess symptoms of depression, anxiety, and stress. This questionnaire is composed of 21 items rated on a 4-point Likert scale (0 – did not apply to me at all; 3 – applied to me very much or much of the time), to which the participants must report how much each item has applied to them in the past week. The combined ratings result in 3 scores, one for each sub-scale, ranging from 0 to 21. Higher scores reflect more negative affective states (Pais-Ribeiro et al., 2004). Internal consistency levels were calculated for each subscale: Anxiety (α = .77), Depression (α = .81), and Stress (α = .88).

Positive Affect and Negative Affect Schedule (PANAS)

Participants completed the Portuguese version (Galinha & Pais-Ribeiro, 2005) of the PANAS (Watson et al., 1988), a 20-item instrument with two sub-scales: positive affect and negative affect. Each item refers to a positive or negative emotion, to which participants must report how much that emotion was felt (ranging from 1 – "very slightly or not at all" to 5 – "extremely") at both the moments of baseline and post-intervention assessments. An additional self-report section was added to this assessment, namely an evaluation of aspects of task difficulty, usability and confidence, and general relaxation and connection to one's body, using a numerical rating scale ranging from 0 to 10. Participants were also invited to write about their subjective experience during the session (e.g., insights on their performance, effects on relaxation).

2.3. Experimental Tasks

Emotion Representation Task (ExpressionMap)

This task is a novel experimental paradigm aimed at indexing the precision and differentiation of visual emotional representations, which are particularly important abilities in reading other's emotions (Keating & Cook, 2022, pre-print; Keating et al., 2023). The stimuli were dynamic point-light faces (PLFs), that is, dynamic (i.e., moving at different speeds) displays of facial expressions (recorded by actors), made up of small dots and expressing different emotions with variable kinematic and temporal-based (i.e., speed) features. The underlying principle is that participants with less precise representations would attribute more variable speeds to the facial expressions. Additionally, participants with highly overlapping representations of the speed of each emotion would attribute more similar speeds to the facial expressions than those with more distinct internal representations of those emotions (Keating & Cook, 2022; Keating et al., 2023). The task was translated into Portuguese and performed online through the Gorilla platform (preview available at https://app.gorilla.sc/openmaterials/447800).

During each trial, participants viewed a dynamic PLF representing 3 different emotional facial expressions (i.e., angry, happy, sad), in loops of around 6 seconds. Each loop was first presented at a random speed, so that participants could adjust the speed of the facial expression, by using a dial, so it could match a typical expression of the presented emotion. There were 16 loops for each emotion, made up of 4 repetitions performed individually by 4 actors, resulting in a total of 48 trials (as well as 3 training trials). Each trial occurred at the participant's own pace.

Baseline Cardiac Measurement Task (Vanilla Task)

This is a color detection task intended to measure baseline cardiac function. This task differs from conventional resting-state baseline measurements in the sense that it is stimulus-oriented, albeit with low cognitive demand (Jennings et al., 1992). Participants were presented with a sequence of 50 randomly colored squares on a tablet screen (each one for the duration of 10 seconds, and intercalated with a 2-second fixation cross) and were asked to silently count all the light blue squares in the sequence and report the number at the end, though the response itself was not relevant for the purposes of the task (i.e., baseline cardiac measurement). The task was built on PsychoPy v2022.2.5 (Peirce et al., 2022).

Heartbeat Discrimination Task

This interoceptive discrimination task (Katkin et al., 1983) involved the presentation of heartbeat sounds to participants in a condition of synchrony or asynchrony with their actual heartbeat. In each trial, participants reported whether the *heard* heartbeat (i.e., heartbeat sound) is in synchrony with their *felt* heartbeat (i.e., actual heartbeat), which renders an index of IAcc. Participants also provided confidence rating for each trial using a Visual Analogue Scale (VAS) ranging from 0 (not confident at all) to 10 (very confident), which corresponds to an index of IS.

Participants heard, through headphones, ≈10 consecutive heartbeats per trial, for a total of 20 trials. Of these 20 trials, half were synchronized with the actual heartbeat, while the other half were delayed by an interval of 500ms and presented in a randomized order. Participants were encouraged to complete the trials at their own pace and take their time to focus on their *felt* heart between trials, signaling the investigator once they are ready for the next one. This task was completed at baseline and after the intero-exteroceptive attention task.

Intero-Exteroceptive Attention Task & Task Modulation

During this task, each participant underwent a period of 10 minutes of sensory exposure, relaxation, and mindful attention, according to their own experimental group (i.e., interoceptive, exteroceptive, intero-exteroceptive). Cardiac data was recorded throughout this period.

The interoceptive attention task was based on heartbeat attention tasks (Petzschner et al., 2019), in the sense that participants were asked to close their eyes and focus their attention on their own heartbeat, as well as subsequent thoughts and emotions, returning their attention to the heartbeat when it eventually drifts away. Participants used noise-cancelling headphones with no sound to minimize unwanted noise from outside.

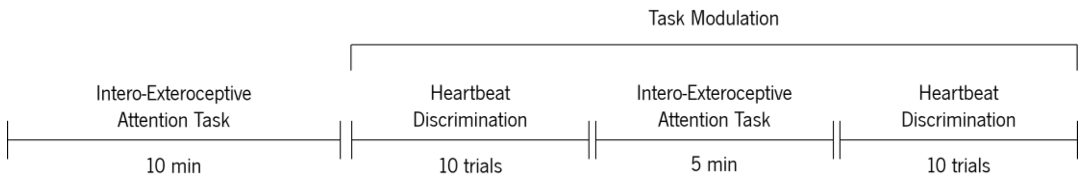
The exteroceptive attention task was a music listening task using a recording of the interactive music system (described below) at a fixed tempo (60 beats per minute) and without any heartbeat sounds (thus defined as non-interactive). Participants were invited to relax, close their eyes, and focus their attention on the sounds and textures within the ambient music, while allowing for subsequent thoughts and emotions to arise.

The intero-exteroceptive attention task used the interactive music system, i.e., ambient music produced via generative algorithms in real-time by the participant's heartbeat sounds captured by a microphone, thus rendering the exteroceptive stimulus (i.e., music and *heard* heartbeat) temporally aligned and integrated with the interoceptive signal (e.g., *felt* heartbeat). During this period, participants were invited to relax, close their eyes, and focus their attention dynamically between the ambient music (e.g., sounds, textures) and their own heartbeats (both *heard* and *felt*), while allowing for subsequent thoughts and emotions to arise.

To potentiate the effects of this task, a shorter period (5 minutes) of stimulation (as per each participant's experimental group) was introduced in the middle of subsequent heartbeat discrimination task, thus further modulating task performance (Fig. 1; Leganes-Fonteneau, 2021).

Figure 1

Procedure for the Intero-Exteroceptive Attention Task & Task Modulation



2.4. Data Acquisition

Cardiac Data Recording

Cardiac data (i.e., heart rate [HR] and RR intervals) was collected using the Polar H10 heart monitor (Polar Electro Oy, Kempele, Finland; sampling rate: 1000 Hz), which has been validated as a sound method to assess RR intervals and subsequent HRV analysis, as compared to conventional ECG equipment (Gilgen-Ammann et al., 2019; Schaffarczyk et al., 2022). The heart monitor was placed around the participant's chest, in contact with the skin, with an adjustable strap. The Polar H10 was paired via Bluetooth to a computer.

Heartbeat Audio Recording

For this study's paradigm, participants' heartbeat sound was recorded, to be used both in the heartbeat discrimination task and in the interactive music system. Most studies employing the heartbeat discrimination task transform the R-peaks measured from continuous ECG recording into acoustic tones (Katkin et al., 1983). However, based on studies that use real heartbeat sounds in the study of interoception and emotion recognition (e.g. Kleint et al., 2015; Lenggenhager et al., 2013; Xiefeng et al., 2019), as well as on phonocardiography (PCG) techniques (Ismail et al., 2018), real-time heartbeat audio recording was employed to explore the ecological validity and potential of using this approach on interoceptive-based tasks and interactive music systems.

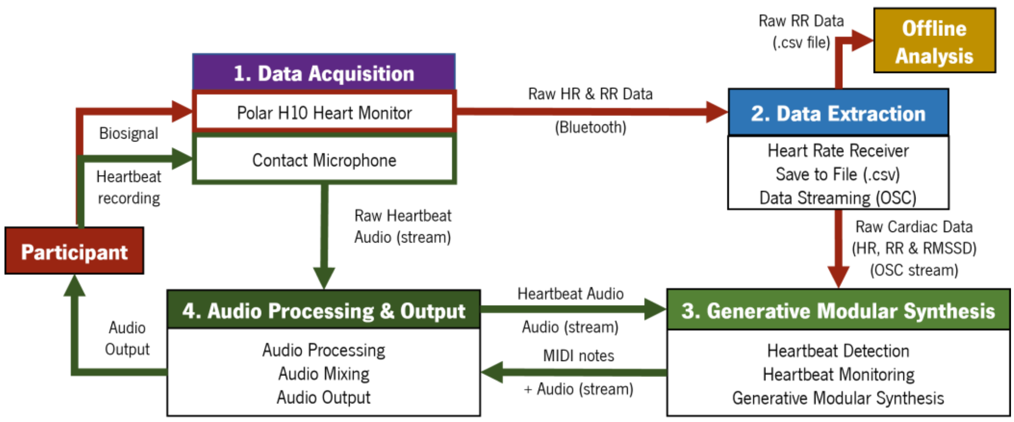
Heartbeats were recorded using a C-Series Pro contact microphone (Jez riley French, United Kingdom), which was designed to sense sound vibrations through contact with solid objects, covering a wide range of frequencies, with low noise. The contact microphone was connected to an audio interface (Roland Rubix22; Roland Corporation, 2017) and kept at a standard gain level (≈ 65%). To further optimize the heartbeat sound quality (i.e., reduce noise and movement), participants were laid in the supine position and the microphone was placed in contact with the skin around the mitral area of the chest and tucked under the Polar H10 chest strap for stability.

2.5. Interactive Music System

The interactive music system developed for this study follows a modular design (Fig. 2), consisting of modules for 1) data acquisition, 2) data extraction, 3) generative modular synthesis, and 4) audio processing and output.

Figure 2

Interactive Music System Modular Design

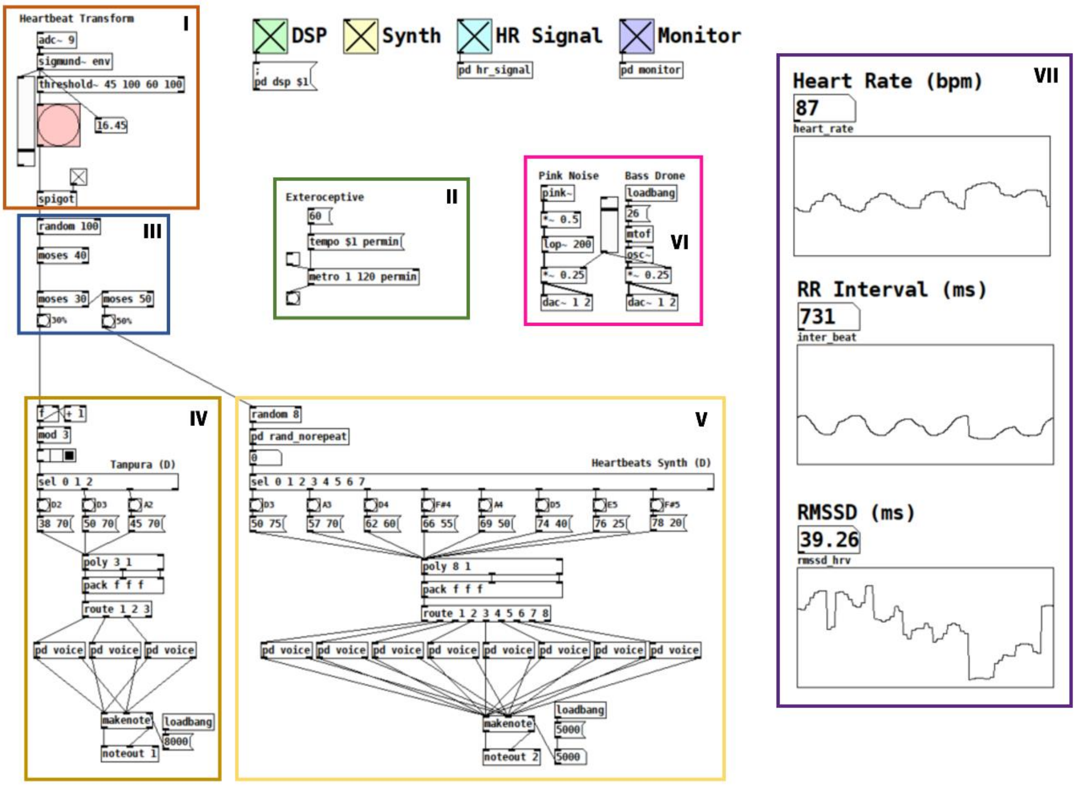


The (1) data acquisition module recorded cardiac data (i.e., HR and RR data) which was then streamed to the (2) data extraction module via Bluetooth. The heartbeat audio recording was streamed to the (4) audio processing module via an audio interface (Roland Rubix22). The software used in the (2) data extraction module was Neuromore (2023), a free neuro and biofeedback streaming and processing tool. Here, cardiac data was received, saved for offline analysis (i.e., exported into a .csv file with RR data), processed in real time (e.g., RMSSD calculation using a 10s RR-interval window), and streamed via Open Sound Control (OSC) protocol into the (3) generative modular synthesis module (see Fig. 3 for a detailed description).

Figure 3

Generative Modular Synthesis Module

[I] *Incoming heartbeat sounds pass through a threshold to identify R-peaks, triggering a 'bang' object (i.e. pink circle), and, in turn, generate signals that simultaneously trigger subsequent 'bangs' (i.e., smaller circles);* **[II]** *A meter generating 'bangs' at a set rate of 60 bpm for the exteroceptive condition;* **[III]** *A probability distribution set to attenuate the rate of activation of the generative algorithms;* **[IV]** *A polyphonic sequencer algorithm generating low-frequency MIDI notes with long decay;* **[V]** *A generative polyphonic algorithm producing medium to high-pitched soft MIDI notes with long decay;* **[VI]** *A continuous drone ambience consisting of pink noise and a very-low-frequency note;* **[VII]** *A visual module to monitor cardiac data in real time.*



This module (3) was created in Pure Data (PD; Puckette, 1996), an open-source visual programming language for multimedia applications. Algorithmic functions are represented by objects (visual boxes), each with their task (e.g., triggers, mathematical operations), communicating between themselves via patch cords. PD allows incoming and outgoing audio, MIDI (i.e., Musical Instrument Digital Interface), and OSC streams from/to external systems, such as the (2) data extraction and (4) audio processing modules mentioned above.

The rationale for the ambient music generated by this module was based on the design principles outlined in Leslie et al. (2019): unobtrusiveness of the system on attention, avoidance of familiarity with the music, and the ability to invite a relaxation response. This also aligns with Eno's (1978) definition of ambient music mentioned above, namely, the ability to "induce calm" and "accommodate many levels of listening attention without enforcing one in particular". In this sense, incoming heartbeat sounds, and corresponding data signals were attenuated to allow space between triggered notes, thus creating a calm musical environment. Additionally, the notes triggered within the generative algorithms were chosen based on harmonic stability and emotional ambiguity (i.e., unfamiliarity). A continuous ambiance consisting of pink noise and a low bass drone also contributed to a calm and immersive musical environment.

The (4) audio processing and output module was created using Reaper (Cockos Incorporated, 2023), a free-to-use digital audio workstation. Incoming heartbeat sounds were filtered and compressed to achieve a clear sound to be used in the (3) generative modular synthesis module (via audio stream) and the ambient music mix, so that participants could listen to their own heartbeats along with the music. Incoming MIDI signals from PD controlled synthesizers and effect units within Reaper, engineered and mixed to create soft and wide resonating sounds. The heartbeat sounds were also used to conduct the heartbeat discrimination task, creating a duplicate track fitted with a 500ms delay, thus creating its asynchronous condition. Participants listened to the audio output through noise-cancelling headphones.

2.6. Procedure

The study was approved by the Ethics Committee for Research in Social and Human Sciences of the University of Minho (CEICSH 043/2023). The recruitment process was done through informal advertisement (using a snowball sampling approach), flyers distributed in university spaces and posted in social media, and through the SONA credit platform of the UM. As explained above, participants first completed the screening questionnaire, the self-assessment reports, and the emotional representation task (ExpressionMap), via online platforms (See Fig. 4).

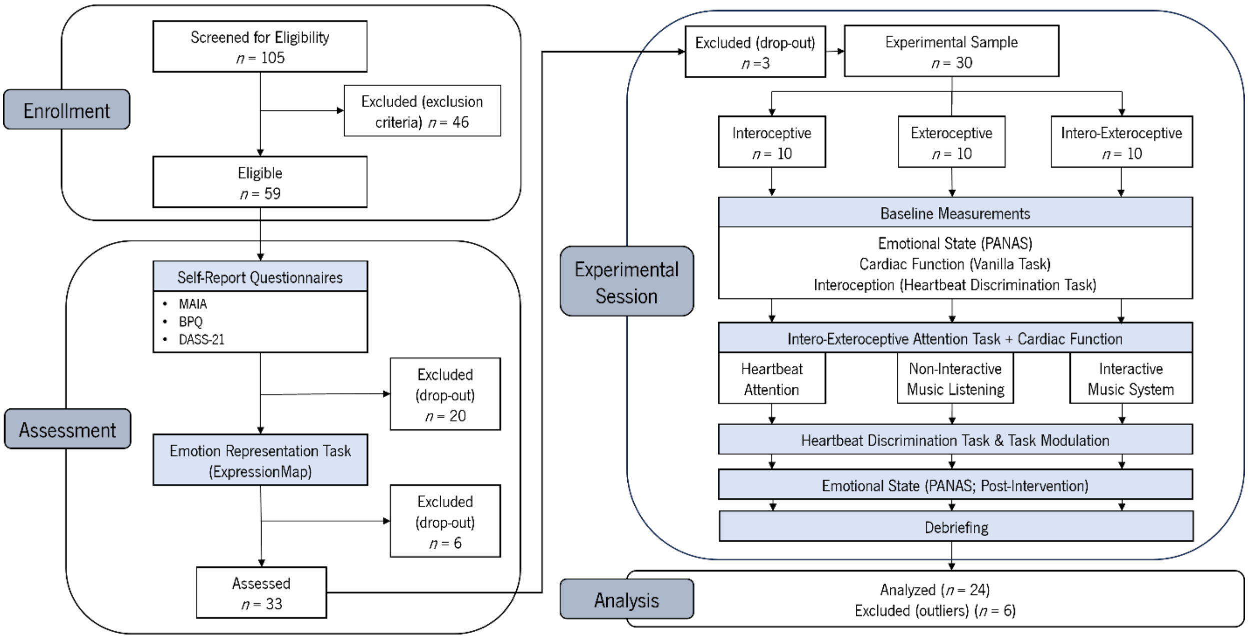
On the day before the scheduled experimental session, participants were contacted by the investigator via SMS to confirm their attendance and asked to not consume alcohol, stimulants (e.g., coffee, nicotine) or heavy meals before the experiment. On the day of the experiment, participants were given an overview of the experiment and then provided signed informed consent.

The session started with the baseline assessment of emotional state (PANAS). Next, participants were instructed on how to equip the Polar H10 heart monitor and then were laid on a reclinable massage table with their head elevated and were presented with a tablet to complete the Vanilla task for baseline cardiac data recording (10 minutes). Once this task was completed, participants were instructed on how to equip the contact microphone and asked to be laid in a supine position. The microphone's position was calibrated as needed to achieve a clear heartbeat sound. After this testing period, participants were given headphones and received instructions for the baseline assessment of the heartbeat discrimination task, which started with 3-4 test trials, and then the 20 main baseline trials. Since participants were encouraged to do this task at their own rhythm, the task duration varied around 10 to 15 minutes.

Following the baseline assessment, and according to each participant's experimental group, the intero-exteroceptive attention task took place after providing the relevant instructions and calibrating the music system (for the exteroceptive and intero-exteroceptive groups) for proper functioning and adjusting the volume to a comfortable level for the participant (higher volume within comfortable levels was recommended to maximize exposure to low-frequencies). This task was carried out for 10 minutes and cardiac data was recorded throughout. Next, participants completed the first half of the heartbeat discrimination task (10 trials), followed by 5 minutes of the attention task (to potentiate its effects; Leganes-Fonteneau et al., 2021), and then completed the other half of the heartbeat discrimination task (10 trials), with a total duration ranging from 15 to 20 minutes. Lastly, participants completed the post-intervention assessment of emotional state (PANAS) and a short debriefing took place to assess any possible adverse effects of the experience on their emotional integrity and discuss any relevant aspects of their subjective experience throughout the task (see Fig. 4 for full schematic). After completing all phases of the study, participants that were recruited through UM's SONA credit platform.

Figure 4

Flow Diagram (as per CONSORT 2010 guidelines) of the full procedure



2.7. Data Analysis

ExpressionMap

Data from ExpressionMap (Keating & Cook, 2022, pre-print) was processed through a custom script made available online by the author, rendering mean scores of consistency or precision of visual emotion representations, distance or overlap between emotions, and confidence ratings.

Cardiac Data

RR data was extracted from Neuromore and then imported into ARTiiFACT 2.13 (Kaumann et al., 2011) for preprocessing (i.e., artifact detection and correction) and subsequent HRV analysis. ARTiiFACT is a freely available tool for heart rate processing and HRV analysis. ARTiiFACT has shown better artifact detection rate and fewer false detections when compared to conventional HRV analysis products such as Kubios® (Tarvainen et al., 2014; Kaufman et al., 2011). Due to incomplete data, 5-minute intervals were first extracted from the 10-min Vanilla task and the intero-exteroceptive attention task data, considering an initial buffer period of 120 seconds. Next, artifacts were detected using the Berntson algorithm (Berntson et al., 1990) and processed using cubic spline interpolation to replace inaccurate interbeat intervals (IBIs). Rather than using a threshold-based criteria for artifact detection (e.g., IBIs above or below median/mean), the Bernston algorithm applies a percentile-based approach to detect and remove artifacts (Berntson et al., 1990; Kaufmann et al., 2011).

For each experimental phase (baseline and intero-exteroceptive attention task), mean HR was extracted as an index of arousal (Raz & Lahad, 2022), as well as log-transformed time-domain and frequency-domain HRV indices reflecting vagal tone and parasympathetic activity dynamics (Laborde et al., 2017). In the time-domain, the natural logarithm of the root mean square of successive differences (lnRMSSD) has been shown to reflect vagal tone, as well as, in the frequency-domain, the natural logarithm of the power (ms^2) of the high-frequency (lnHF) band (ranging from 0.15 to 0.4 Hz), which is also associated parasympathetic activity and variations in heartbeat associated with the respiratory cycle (Laborde et al., 2017; Shaffer et al., 2014). As described in Leganes-Fonteneau et al. (2021), we also considered the natural logarithm of the peak power in the resonance frequency of the cardiovascular system (ln 0.1 Hz HRV in ms^2; ranging from 0.075 to 0.108 Hz) as it reflects HRV within a narrow frequency band, that is, a narrowing of cardiac variability within a predictable afferent oscillatory pattern, thought to improve interoceptive accuracy by potentially reducing prediction errors.

Interoceptive Measures

Data extraction for interoceptive dimensions (i.e. IS, IAcc, IAw) followed the procedures outlined in Garfinkel et al. (2015; Bekrater-Bodmann et al., 2020). IAcc was extracted by calculating the relative number of correct trials from the heartbeat discrimination task, rendering an accuracy measure ranging from 0 (no correct trials) to 1 (all trials are correct) (Garfinkel et al., 2015; Bekrater-Bodmann et al., 2020). IS was determined by calculating the mean confidence rating for each of the trials' performance, then dividing it by 10 to achieve a value ranging from 0 (very unconfident) to 1 (very confident) (Garfinkel et al., 2015; Bekrater-Bodmann et al., 2020). Lastly, IAw (i.e., metacognitive awareness of interoceptive abilities) was determined by analyzing the degree to which interoceptive sensibility can predict interoceptive accuracy (Garfinkel et al., 2015; Bekrater-Bodmann et al., 2020; Leganes-Fonteneau et al., 2021). To achieve this, a receiver operating characteristic (ROC) curve analysis (Green & Swets, 1966) was employed, using the area under the ROC curve (AUROC) as an index of the association between confidence (test variable) and performance (i.e., correct trials; state variable) (Garfinkel et al., 2015). The hit rate (correct performance and high confidence) was plotted against the false alarm rate (incorrect performance and high confidence), thus accounting for individual bias in reporting high or low confidence (Garfinkel et al., 2015; Bekrater-Bodmann et al., 2020).

Data Transformation

Using a combination of standard and modified z-scores (Iglewicz & Hoaglin, 1993), and Tukey's Boxplot (Tukey, 1977) methods for outlier detection (Shein & Fitrianto, 2017), 6 outliers (2 per experimental group) were identified and removed, resulting in a sample size of N = 24. Distribution of the data was tested using the Shapiro-Wilk test, while also consulting z-scores for both skewness and kurtosis (Kim, 2013), both at a general level and at group level. Several non-normally distributed variables were found, specifically on self-report measures (MAIA and DASS-21), mean confidence ratings from ExpressionMap, and state emotional measures (PANAS). Data transformation was employed on these measures. Furthermore, specific assumptions for the planned analyses were tested and met for all variables of interest (i.e. normality of residuals, sphericity, homogeneity of variance). However, despite data transformation, subjective emotional measures did not meet the required assumptions, thus we resorted to non-parametric tests for their analysis (e.g., Kruskal-Wallis H test).

Data Analysis

The software IBM® SPSS Statistics (28.0.0.0, 190; IBM Corp. ©, 2021) was used to analyze the data. First, preliminary exploratory analyses were performed to test assumptions (e.g., outlier detection, normality). Descriptive statistics were employed to characterize the sample and to assess the feasibility and usability of the interactive music system using self-report items about the participants' subjective experience at the end of the intervention.

To analyze the effects of the intero-exteroceptive task on interoception, cardiac function (HR and HRV), and emotional state measures, a mixed ANOVA with within- (i.e., time: baseline [T1] and during the intero-exteroceptive attention task [T2]) and between-subjects (i.e., experimental group) factors was performed. Next, cardiac function, self-reported interoception, psychopathology, and emotion representation variables were used as covariates in the ANOVA models mentioned above (including the difference between within-subjects variables [Tdiff]), to verify their significance on the observed effects. If the effects were maintained, a moderation analysis was performed using the MEMORE macro for SPSS (v2.1; Montoya, 2019) to further probe the predictive or moderating role of these variables on the effects of the intero-exteroceptive task. In this analysis we used the repeated measures as the outcome variable (T1 as the focal predictor [X] and T2 as outcome variable [Y], as well as their difference [Ydiff]), and the experimental groups and variables of interest as the moderators (W).

To analyze the predictive role of the variables of interest, we employed a linear regression analysis, considering the scores of the self-report questionnaires (i.e. MAIA, BPQ, DASS-21), the results from ExpressionMap (i.e., emotion representation precision and differentiation, as well as mean confidence rating), and the within-subjects variables outlined above (T1, T2, and Tdiff). Finally, a simple feasibility and usability analysis was applied to understand the participants' assessment of the experimental task.

3. RESULTS

3.1. Effects of the Intero-Exteroceptive Attention Task on Interoception, Cardiac Function & Emotional States

Separate mixed ANOVAs with within-between subjects' factors were conducted to examine the effect of the intero-exteroceptive attention task on interoceptive measures (IS, IAcc, and IAw) and cardiac function (HR, lnRMSSD, lnHF, ln 0.1 Hz HRV) across time and between groups (i.e., interoceptive, exteroceptive, and intero-exteroceptive). See Table 1 below for results.

Table 1

Mixed ANOVAs with within-between subject's factors on the effects of the Intero-Exteroceptive Attention Task on Interoception and Cardiac Function

	Measure	*df*	*F*	Sig.	η^2
Within-subjects effects					
Time	HR	1,21	73.444	< .001	.778
	lnRMSSD	1,21	14.445	.001	.408
	lnHF	1,21	8.629	.008	.291
	ln 0.1 Hz HRV	1,21	8.965	.007	.299
Time x Group	IAcc	2,21	4.527	.023	.301
Between-subjects effects					
Group	IS	2,21	3.550	.047	.253

We found an interaction effect between time and experimental conditions in IAcc. Pairwise comparisons between groups and time revealed that differences in IAcc were significantly higher in the intero-exteroceptive group (mean difference = -1.44, 95% CI [-.236, -.052], p = 0.004) in comparison to other groups across time.

In terms of the effects of the attention tasks on cardiac function, main effects were found for all variables across time. Separate pairwise comparisons between groups and time revealed: 1) significantly higher differences in HR in the intero-exteroceptive group (mean difference = 11.084, 95% CI [7.330, 14.839], $p < 0.001$) than in the interoceptive (mean difference = 7.872, 95% CI [4.118, 11.626], $p < 0.001$) and exteroceptive (mean difference = 7.841, 95% CI [4.087, 11.596], $p < 0.001$) groups; 2) significantly higher differences in lnRMSSD in the intero-exteroceptive (mean difference = -.378, 95% CI [-.673, -.084], $p = 0.014$) than in the interoceptive group (mean difference = -.339, 95% CI [-.634, -.044], $p = 0.026$); 3) significant differences in lnHF only in the intero-exteroceptive group (mean difference = .815, 95% CI [.206, 1.242], $p = 0.011$); 4) significant differences in ln 0.1 Hz HRV only in the interoceptive group (mean difference = -1.120, 95% CI [-1.998, -.241], $p = 0.015$).

Additionally, two separate Kruskal-Wallis H tests were employed to examine differences in state emotional measures indexed by PANAS (positive and negative affect) across time and between experimental conditions, respectively. Significant differences were found only in negative affect across time ($H(1) = 4.187$, $p = .041$), with mean rank scores of 28.31 for T1 and 20.69 for T2, indicating a decrease in negative affect across time for all conditions.

3.2. Moderating Role of Cardiac Function, Self-Reported Interoception, and Psychopathology on Interoceptive Accuracy

As described in the data analysis pipeline, the moderation models were carried out after testing for the maintenance of the time x experimental group interaction effect (intero-exteroceptive group) observed in the mixed ANOVA model when using the variables of interest as covariables.

To explore the moderation and subsequent conditional effects of cardiac measures upon the increases in IAcc, a moderation analysis was performed using IAcc at T2 as the dependent variable (Y), IAcc at T1 as the independent variable (X) while their difference constituted the outcome variable (Ydiff). The moderators included the experimental group (W_1) to account for the interaction effect observed above with the intero-exteroceptive condition ($W_1 = 3$), while two subsequent moderator variables were employed, namely task-based (T2) cardiac measures (W_2) and their difference between T2 and T1 (W_3). The rationale for these latter moderator variables was identifying at which degree (i.e., low, moderate, high) of T2 cardiac measures (W_2) did we find most significant improvements in IAcc, while, at the same time, identifying how the differences in cardiac measures between T2 and T1 (W_3) reflected different directions of change (i.e., attenuation or enhancement), and thus how they accounted for these improvements at different degrees.

Additional moderation models were employed to investigate the moderating role of self-reported interoception (MAIA) and psychopathology (DASS-21) on the improvements in IAcc in the intero-exteroceptive group. See Table 2 for full results.

Table 2

Moderation Analysis of the role of Cardiac Function, Self-Reported Interoception (MAIA), and Psychopathology (DASS-21) on the improvements in Interoceptive Accuracy

Moderators	Model Summary				Conditional Effects						
	R^2	df	*F*	Sig.	W_1	W_2	W_3	W_4	Effect	*t*	Sig.
*Cardiac Function**											
HR	.475	3,20	6.032	.004	3[a]	59.29[1]	-14.05[3]		.19	3.967	.001
lnRMSSD	.398	3,20	4.405	.016	3[a]	4.447[3]	-.079[3]		.20	3.499	.002
lnHF	.418	3,20	4.790	.011	3[a]	7.932[3]	-.334[3]		.19	2.989	.007
ln 0.1 Hz	.323	3,20	3.266	.043	3[a]	6.969[3]	-.466[3]		.17	2.348	.029
*MAIA***	.452	4,19	3.920	.017	3[a]	3.166[1]	3.671[3]	2.630[1]	.29	3.070	.006
					3[a]	3.166[1]	3.671[3]	3.611[2]	.30	3.518	.002
					3[a]	3.166[1]	3.671[3]	4.592[3]	.30	3.497	.002
*DASS-21****											
Anxiety	.300	2,21	4.496	.024	3[a]	1.258[1]			.13	2.595	.017
					3[a]	5.542[2]			.12	3.368	.003
					3[a]	9.825[3]			.12	2.903	.009
Depression	.300	2,21	4.489	.024	3[a]	.568[1]			.12	2.654	.015
					3[a]	4.292[2]			.12	3.386	.003
					3[a]	8.016[3]			.12	2.861	.009

* W_1 = experimental group; W_2 = T2 cardiac measures; W_3 = difference in cardiac measures between T2 and T1.
** W_1 = experimental group; W_2 = Emotional Awareness (MAIA); W_3 = Self-Regulation (MAIA); W_4 = Trusting (MAIA).
*** W_1 = experimental group; W_2 = DASS-21 scores (Anxiety and Depression).
[a] W_1 = 3 (intero-exteroceptive group).
[1] Low; [2] moderate; and [3] high moderator (W) values.

Together, these results suggest that improvements in IAcc were significantly more effective in the intero-exteroceptive group: 1) at lower HR and higher HRV task-based cardiac measures, especially when accompanied by greater attenuation of HR and HRV; 2) at low levels of Emotional Awareness, high levels of Self-Regulation, and across low, moderate, and high levels of Trusting; and 3) across low, moderate, and high levels of Anxiety and Depression.

3.3. Moderating Role of Self-Reported Interoception on Cardiac Function

To further expand on the main effect observed in cardiac measures, we employed separate moderation models using the experimental conditions and dimensions of the MAIA and DASS-21 as moderators. We found that Trusting was a particularly significant moderator across time and all groups and most cardiac measures: 1) HR (R^2 = .404, F(2,21) = 7.117, p = 0.004); 2) lnRMSSD (R^2 = .466, F(2,21) = 9.174, p = 0.001); and 3) lnHF (R^2 = .292, F(2,21) = 4.341, p = 0.026). Conditional effects analysis revealed that lower Trusting values yielded significantly higher improvements in each cardiac measure, with greater effects observed in the intero-exteroceptive condition for both HR and lnHF, and the interoceptive condition for lnRMSSD.

3.4. Individual Differences: The Role of Psychopathology

Using a linear regression analysis on the psychopathological measures indexed by DASS-21, we explored individual differences and the predictive role of self-reported interoception indexed by MAIA, BPQ, and interoceptive and cardiac baseline measures.

With regards to Anxiety, a regression model using the Self-Regulation and Trusting dimensions of the MAIA as predictors was significant (adjusted R^2 = .328, F(2, 22) = 6.605, p = 0.006), with separate models testing each predictor: 1) Self-Regulation (ß = -.610, t(23) = -3.608, p = .002) and 2) Trusting (ß = -.494, t(23) = -2.668, p = .014).

For Depression, the same model yielded significant results (adjusted R^2 = .320, F(1, 22) = 11.843, p = 0.002), with separate models testing each predictor: 1) Self-Regulation (ß = -.518, t(23) = -2.840, p = .010) and 2) Trusting (ß = -.564, t(23) = -3.207, p = .004). An additional regression model using baseline IAcc as a predictor was also significant (adjusted R^2 = .320, F(1, 22) = 11.843, p = 0.002; ß = -.592, t(23) = -3.441, p = .002).

Finally, we found that the Self-Regulation dimension of the MAIA significantly predicted Stress (adjusted R^2 = .243, F(1, 22) = 8.376, p = 0.008; ß = -.525, t(23) = -2.894, p = .008).

3.5. Individual Differences: The Role of Emotion Representation

Using a linear regression analysis on the emotion representation measures indexed by ExpressionMap (mean confidence ratings, mean distance between emotions, mean representational precision), we explored individual differences and the predictive role of measures indexed by MAIA, BPQ, DASS-21, and interoceptive and cardiac baseline measures.

Regression models employing MAIA's dimensions of Not-Distracting and Emotional Awareness as predictors were significant with regards to mean confidence ratings (adjusted R^2 = .371, F(2, 23) = 7.773, *p* = 0.003) and mean distance between emotions (adjusted R^2 = .331, F(2, 23) = 6.702, *p* = 0.006). Separate models were tested for each variable and each predictor, yielding significant results for: 1) mean confidence ratings: Not-Distracting (ß = -.523, t(23) = -2.877, *p* = .009) and Emotional Awareness (ß = .581, t(23) = 3.717, *p* = .013) ; 2) mean distance between emotions: Not-Distracting (ß = -.480, t(23) = -2.566, *p* = .018) and Emotional Awareness (ß = .581, t(23) = 3.347, *p* = .003).

With regards to mean representational precision, the regression model employing all MAIA dimensions was significant (adjusted R^2 = .339, F(7, 23) = 2.686, *p* = 0.048). Due to strong multicollinearity in this model, separate models were tested for each predictor, yielding significant results for Emotional Awareness (ß = -.538, t(23) = -2.993, *p* = .007), Self-Regulation (ß = -.308, t(23) = -2.097, *p* = .048), and Trusting (ß = -.492, t(23) = -2.654, *p* = .014).

With respect to DASS-21 scores, the regression model was significant for all measures (adjusted R^2 = .283, F(3, 23) = 4.030, *p* = 0.022), while separate models revealed Anxiety (ß = .515, t(23) = 2.817, *p* = .010) and Depression (ß = .444, t(23) = 2.323, *p* = .030) as significant predictors.

3.6. Feasibility & Usability Analysis

A short questionnaire was employed to evaluate general aspects of the intero-exteroceptive task, the feasibility of using real-time heartbeat sounds, and self-perception about relaxation and connection to one's body and heart. Participants reported a moderately high degree of clarity in being able to listen to heartbeat sounds (*M* = 7.42, *SD* = 1.767) and moderate general confidence (*M* = 6.04, *SD* = 1.732) and difficulty (*M* = 5.98, *SD* = 2.324) in performing the intero-exteroceptive attention task.

4. DISCUSSION

In this study, we aimed at developing an interactive music system and providing a proof-of-concept examination of its effect on interoception, cardiac function, and subjective emotional states, while, at the same time, exploring the relationship between these effects and subjective aspects of interoception, psychopathology, and emotion representation.

As hypothesized, the use of the interactive music system in the intero-exteroceptive attention task resulted in significant improvements in IAcc, decreases in physiological arousal (i.e.

HR) and subjective negative emotional states, and enhanced HRV (i.e., lnRMSSD, lnHF). Together, these results suggest that the ambient music environment generated by the interactive music system, through its multisensory integration and temporal synchronization of interoceptive and exteroceptive signals, induced calm and relaxed physiological states (i.e., relaxation response), while also increasing one's ability to accurately discriminate between synchronous and asynchronous interoceptive (i.e., cardiac) and exteroceptive (i.e., auditory) signals. As informed by predictive coding theories/models (Seth, 2013, 2021) and temporo-spatial neuroscience (Northoff et al., 2023; Tumati et al., 2021), this increase in IAcc may be the result of the reduction of prediction errors and afferent "noise" afforded by the temporal synchronization of interoceptive and exteroceptive signals and subsequent dynamical entrainment of participants to their own cardiac rhythms.

Of note, we found that the intero-exteroceptive condition was significantly more effective in increasing IAcc, by revealing greater increases when participants demonstrated low HR and high HRV levels in the task-modulation phase, accompanied by HR attenuation and HRV suppression during the intero-exteroceptive attention task. As proposed by Corcoran and colleagues (2021), cardiac deceleration and stabilization (i.e., HR attenuation and HRV suppression) might be pivotal in promoting sensory processing of stimuli, by rendering cardiac activity more predictable and thus resolving the uncertainty of bodily state dynamics. Assuming a predictive coding perspective, this uncertainty reduction could also be interpreted as the reduction of prediction errors (Seth, 2013, 2021). This cardiac dynamic can be further defined as a process of *attentional bradycardia,* known to play an instrumental role in aiding "both the organism's receptivity to afferent stimulation and the organism's readiness to make effective responses to such stimulation" (Lacey, 1972, p. 183). Interestingly, in this study, we observed that, although IAcc increased in instances of HR attenuation and HRV suppression, this occurs at low HR and high HRV levels, respectively, corresponding to the relaxation response. High HRV, specifically, might have a beneficial effect in recruiting heartbeat dynamics and to resolve uncertainty, as the opposite occurs in blunted HRV (Corcoran et al., 2021).

This process of cardiac deceleration and stabilization at high HRV levels also reflects how the relaxation response can be maintained while allocating attention to interoceptive and exteroceptive signals, thus stabilizing physiological dynamics and reducing vulnerability to maladaptive attentional states and related psychopathological symptoms. This could be observed in our results through the improvements in IAcc in the intero-exteroceptive condition despite different levels of anxiety and depression. We were also able to observe the moderating effects of attentional and regulatory styles on these improvements, namely, the effects of Emotional Awareness, Self-Regulation, and Trusting. These dimensions of the MAIA are thought to reflect an overall mindful attentional and regulatory style in interoceptive awareness (Mehling, 2016). Regarding the interaction between Emotional Awareness and Self-Regulation, Mehling and colleagues (2012, p. 19) have proposed that 'mere awareness of how body sensations correspond to emotional states, without the ability to use awareness of those sensations to reduce distress, could increase anxiety", meaning that low scores in Emotional Awareness can be related with anxiety-driven attentional styles, without the influence of robust and mindful regulatory styles (i.e. Self-Regulation). Additionally, the Trusting dimension reflects one's attitude towards one's body, especially in experiencing it as trustworthy (i.e. relatively stable) and safe. These observations, along with our results, suggest that mindful attitudes and regulatory styles in interoceptive awareness can effectively lead to optimized awareness and perception of body sensations and their correspondence to emotional states, even when this ability is generally lower, while also reducing one's vulnerability to psychopathology (i.e., anxiety and depression).

Interestingly, a main effect in the relaxation response and reduction of negative affect was observed for all experimental conditions, that is, for the mindfulness-based heartbeat attention task, for the non-interactive music attention task, and the interactive intero-exteroceptive attention task afforded by the interactive music system. This suggests that, although improvements in interoception were not observed for all conditions, they were all equally effective in inducing a relaxation response (i.e., low HR and high HRV) and reducing negative affect in participants. We also observed that the effect of the relaxation response was significantly higher in participants with low Trusting scores (i.e., feeling the body as unsafe and untrustworthy), especially in the intero-exteroceptive condition. One possible explanation is that having direct feedback of one's body state accompanied by a calm and relaxing musical environment might counteract this attitude towards one's body, thus allowing to progressively build trust and feelings of safety by mindful attention to an intero-exteroceptive dynamic environment afforded by the interactive music system.

The inherent algorithmic, musical, and acoustic characteristics of the interactive music system's musical output could also have played an important role in the observed improvements in IAcc and attentional bradycardia. As already proposed in studies using interactive music systems (Leslie et al., 2019; Yu et al., 2018), personalizing the system based on participant's rhythmical physiological oscillations (e.g. breathing, heartbeats), significantly influences their natural physiological patterns and responses, highly contributing in this way for an increased relaxation response across different measures (e.g., reduced HR and enhanced HRV; Yu et al., 2018). Additionally, the predominant low-frequency tones in the ambient music environment may have had a significant influence not only on the entrainment to the intero-exteroceptive rhythmical dynamics (indexed by one's heartbeat), but also on one's perception of their timing. As demonstrated by Hove and colleagues (2014), a *low-voice superiority effect* is observed in the presence of low-frequency tones, which results in enhanced auditory-motor synchronization, perception and encoding of timing, and entrainment of motor movements to a beat, as can be seen in musical contexts where low-frequency instruments (e.g. bass guitar, kick drums) drive the pulse of a song. Expanding on this notion, Viltart and colleagues (2003) have found that cardiac adjustments preparatory to, or concomitant with, motor activity (such as entrainment of motor movements) may start in the motor cortex and then be conveyed to cardiovascular mechanisms. Together, these findings suggest that low-frequency tones may have a significant impact not only on the entrainment of general motor activity to a rhythm, but also of cardiovascular activity. In the dynamic intero-exteroceptive environment afforded by the interactive music system, this may imply an equally dynamic interaction between the motor cortex and cardiovascular system (i.e., neuro-cardiac temporal synchronization), possibly mediated by the INS, with special emphasis on the integrative properties of the insular cortex. Future studies employing neuroimaging could be helpful in further explaining these effects.

In terms of the relationship between interoceptive awareness and social connection, some conflicting results emerged, especially in the negative interaction between the Emotional Awareness, Self-Regulation, and Trusting dimensions of the MAIA with mean representation precision of the ExpressionMap task. As already mentioned, the interaction between Emotional Awareness, Self-Regulation, and Trusting is thought to be a beneficial one, as it reflects an overall mindful attentional and regulatory style in interoceptive awareness (Mehling, 2016). Notwithstanding, its negative relationship with the precision or consistency in representing other's emotions might be counter-intuitive at face-value, as a higher awareness of the connection between emotions and inner bodily states, supported by a higher ability to self-regulate physiologically and feeling one's body as safe and trustworthy, may lead to a greater sensibility in detecting emotional dynamics in others. This is further suggested by the positive relationship between Emotional Awareness and the confidence ratings and distinction between emotions in the ExpressionMap task. However, a possible explanation for these observations might be related to the degree of emotional granularity (i.e., the ability to precisely differentiate emotions; Ventura-Bort et al., 2021), and, at the same time, a potential limitation of the ExpressionMap task. Individuals with high emotional granularity tend to resort to multiple and precise terms to label emotional experiences across the emotional spectrum (e.g., distinguishing between sadness and compassion), while those with low emotional granularity typically rely on a narrow range of terms to describe different emotional experiences (e.g., good/bad, happy/sad) (Ventura-Bort et al., 2021). Since the representational emotional precision scores provided by the ExpressionMap task rely on low variability (i.e., greater consistency) for each typical emotional expression (i.e., anger, happiness, sadness), this may mean that individuals with low emotional granularity may be more successful and consistent due to their binary approach to emotional coding, while those with high emotional granularity might underperform in this task by responding with increased variability to different visual emotional expressions. However, this does not imply that the latter are not able to accurately distinguish between typical emotional expressions, but rather that they may classify them across a wider spectrum (i.e., more variable) in doing so. Together, these observations also align with the proposition that better interoceptive ability and awareness (i.e., mindful attentional and regulatory styles of interoceptive awareness) may translate into richer emotional experiences (i.e., higher emotional granularity), which in turn facilitate the empathic understanding and response to other's emotions, ultimately improving social connection (Arnold et al., 2019).

This relationship between interoceptive attentional styles, emotion representation and emotional granularity might also account for the positive relationship found between anxiety, depression, and representational precision. As suggested by Demenescu and colleagues (2010), there are significant impairments in emotion recognition in both anxiety and major depression disorders, possibly caused by attentional biases. In the case of anxiety, its characteristic avoidant behavior and exacerbated fear of scrutiny in social and emotional context might imply impaired attention allocation to socio-emotional information, based on increased awareness of negatively biased cognitive self-representations and physiological arousal (Folz et al., 2023). With regards to depression, its characteristic exacerbated self-focus and negative cognitions about the self (e.g., self-criticism, hopelessness) might impair their evaluation of external stimuli and, thus, their attention allocation to and recognition of other's emotional dynamics (Demenescu et al., 2010). However, it is not clear how these impairments relate to emotion representational consistency or precision, as consistent emotional representations may indicate, on one hand, accurate representation of a typical emotion or, on the other hand, rigid or prototypical coding of emotion dynamic visual expressions. Conversely, inconsistent (i.e. variable) emotional representations may suggest, on one hand, impairments in accurately representing a typical emotion, or, on the other hand, more flexibility and richness in representing these emotional expressions, as per the perspective of emotional granularity mentioned above (Ventura-Bort et al., 2021).

Our results also demonstrate that these biases may exist not only in attention, but also in terms of regulatory styles, as seen on the negative relationship observed in both anxiety and depression scores, and the Trusting and Self-Regulation dimensions of the MAIA, as well as between IAcc and Depression. These maladaptive attentional and regulatory styles observed in anxiety and depression may reflect impaired intero-exteroceptive attention allocation (Arnold et al., 2019; Tumati et al., 2021), that is, difficulties in flexibly shifting between interoceptive (emotional) and exteroceptive (social) attention, thus negatively contributing to emotional and social dysregulations and, in general, social connection.

Clinical and Research Implications

Overall, this study showed the potential in using interactive music systems for interventions on interoception, cardiac function, and subjective emotional states, yielding significant results within a single session. These, in turn, contributed to the studies using interactive music systems for physiological relaxation (Leslie et al., 2019; Yu et al., 2018), by confirming some of their observed results, and further expanding these findings by demonstrating improvements in interoceptive awareness. Additionally, it showed how mindfulness-based interoceptive attention tasks and adaptive music listening can also be of benefit for improvements in cardiac function and subjective emotional states, as other approaches have already shown, namely, training based on heartbeat perception tasks (Schillings et al., 2022), mindfulness-based body awareness techniques (Fischer et al., 2017; Price & Hooven, 2018), listening to heartbeat sounds (Lenggenhager et al., 2013), and music listening (Reybrouck et al., 2021; Krause et al., 2023). Other important implications are based on the moderating and predictive effects found in terms of mindful vs anxiety-driven attentional and regulatory styles in interoceptive awareness and psychopathology (e.g. anxiety and depression), demonstrating promising avenues of clinical interventions in this respect. These results not only were significant at the individual sphere level, but also showed relations to aspects of social connection, namely in the representation of other's emotions, which can prove useful for targeted interventions on this sphere.

One important implication of the use of interactive music systems as operationalized in this study, is that they are personalizable, relatively easy to manipulate and operate, open-access, affordable, and portable, suggesting a flexibility in employing this system not only in research, but also in clinical contexts. It is especially the personalizable nature of this system that shows most potential, as this can result in more targeted interventions employing different physiological variables (e.g., including cardiac, respiratory, electrodermal, or even electroencephalographic) and multiple parameters and algorithms of interest. The introduction of real-time heartbeat sounds, as based on PCG, also shows an interesting avenue of clinical and research applications.

Limitations

Though this study yielded interesting results, some limitations should be acknowledged. First, the limited sample size distributed along three different experimental conditions may pose a challenge in the data analysis processes, rendering statistical tests less robust. This limitation was due, in part, to difficulties in participants' recruitment and the removal of some outliers. Second, the data collection paradigm used in this study differs from similar studies, which usually employ more robust ECG data collection. Future validation studies between conventional and non-conventional ECG data collection using this paradigm might prove useful to determine their effectiveness. Third, though the resulting improvements were significant within a single-session intervention, it begs the question of replicability in subsequent sessions, as well as of the long-term individual effects of the intervention in the variables assessed in this study. Further studies employing a more longitudinal approach might be valuable in addressing these questions. Finally, this study could have benefited from data collection of other psychobiological modalities, including respiration and electrodermal activity, as well as the levels of absorption and mind-wandering during the intero-exteroceptive task, and measures of personality and emotional regulation and attitudes, especially in the social sphere. Though this would highly increase the already complex nature of the present study, these limitations open new avenues of research within this paradigm.

Future Directions

As already described, this study points to the effectiveness in using interactive music systems to improve interoception, cardiac function, and subjective emotional states in healthy participants, while also showing some possible implications for clinical applications. One possible direction would be applying this paradigm to clinical populations (e.g. anxiety disorders, eating disorders, somatoform disorders) to further verify its effectiveness. Also, employing additional physiological measures and even EEG within the interactive music system could be helpful in crafting new research paradigms in interoception, physiological regulation, and beyond, due to the personalizable nature of these systems. For instance, applying this paradigm in tonotopy-based studies (i.e., spatial mapping of sound frequencies in the brain) may be of particular interest as frequencies can be easily manipulated and integrated with brain dynamics (through EEG), thus allowing to explore potential resonance effects of sound frequencies in different brain areas or circuits. This in turn, would allow for more targeted, accessible, and affordable interventions, involving both physiological and electroencephalographical parameters. Lastly, in terms of social connection, further studies could employ the interactive music systems in *self-other* dynamics, namely by exploring emotional dynamics and physiological synchronization in dyads through biofeedback.

Conclusion

Together, these results demonstrated the effectiveness of interactive music systems in improving aspects of interoception, cardiac function, and subjective emotional states, suggesting that this approach may facilitate intero-exteroceptive integration and temporal synchronization, enhancing one's certainty about bodily states, while inviting mindful attention and calm emotional and physiological states.

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6. ANNEX

Universidade do Minho

Conselho de Ética

Comissão de Ética para a Investigação em Ciências Sociais e Humanas

Identificação do documento: CEICSH 043/2022

Título do projeto: *Integração Multissensorial de Sinais Cardíacos e Auditivos: Implicações na Consciência Interocetiva e Representação Emocional*

Equipa de Investigação: Ricardo Silva (IR), Mestrado Interuniversitário em Neuropsicologia Clínica e Experimental, Escola de Psicologia, Universidade do Minho; Joana Coutinho e Adriana Sampaio (Orientadoras), Centro de Investigação em Psicologia, Escola de Psicologia, Universidade do Minho

PARECER

A Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH) analisou o processo relativo ao projeto de investigação acima identificado, intitulado *Integração Multissensorial de Sinais Cardíacos e Auditivos: Implicações na Consciência Interocetiva e Representação Emocional*.

Os documentos apresentados revelam que o projeto obedece aos requisitos exigidos para as boas práticas na investigação com humanos, em conformidade com as normas nacionais e internacionais que regulam a investigação em Ciências Sociais e Humanas.

Face ao exposto, a Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH) nada tem a opor à realização do projeto nos termos apresentados no Formulário de Identificação e Caracterização do Projeto, que se anexa, emitindo o seu parecer favorável, que foi aprovado por unanimidade pelos seus membros.

Braga, 31 de março de 2023.

A Presidente do Conselho de Ética

(Maria Cecília Lemos Pinto Estrela Leão)