Game-Based Biofeedback Increases Subjective Ratings of Interoceptive Awareness

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***Abstract*—Integrating human physiology into interactive computer environments, game-based biofeedback provides an intuitive platform to learn self-regulation through visualizing, monitoring, and modulating real-time biosignals. The present study presents a novel breath control biofeedback game aimed at enhancing interoceptive awareness–the ability to sense and appraise internal physiological signals–among adolescents and investigated potential differential effects between virtual reality (VR) and flat screen (FS) biofeedback. 45 participants experienced the biofeedback game to practice slow-paced breathing via VR and FS in a randomized order. Findings revealed significant increases in self-ratings of interoceptive awareness concerning the utility of bodily sensations, as well as interconnectedness of mental, emotional, and physiological processes for self-regulation. VR biofeedback may have conferred an added potential benefit through increases in attention regulation scores. While the effects of VR and FS biofeedback did not differ, the order of modality exposure influenced specific interoceptive outcomes. These findings demonstrate the potential of biofeedback games in enhancing interoceptive awareness, with clinical implications for improving emotion regulation and mental health.**

Keywords—Biofeedback, games for health, interoceptive awareness, slow-paced breathing, virtual reality

I. Introduction

Game-based biofeedback combined with slow-paced breathing (SPB) training provides a promising approach to managing physiological responses to stress and thereby reduce anxiety among children and adolescents [1], [2]. It encompasses a close-loop system to measure, monitor, and modulate biosignals in order to reinforce SPB techniques in physiological regulation. Past studies have shown the effectiveness of implementing different breathing patterns under volitional control to achieve temporal coherence of respiratory, blood pressure, and cardiac oscillations [3], [4], [5]. Reducing breathing rate to six cycles per minute (cpm) at the resonant frequency (~ 0.1 Hz) improves vagally-mediated heart rate variability (HRV), an index of cardiac vagal tone associated with self-regulation, emotional stability, cognitive flexibility, and resilience to stress [4], [6], [7], [8]. Increasing cardiac oscillations and vagal stimulations can also activates interoceptive areas influencing the accuracy and awareness of bodily responses [9].

In game-based biofeedback approaches, breath control can be incorporated into game mechanics as a natural input to influence indirectly controlled biosignals (such as HRV). These signals are measured via non-invasive wearable devices, processed in an affective computing system to determine self-regulation performance, then displayed to users for monitoring purposes [10]. Unlike raw numbers or complex waveforms in traditional biofeedback approaches, game-based biofeedback integrates physiological information dynamically in visual or auditory form (or both) as part of the gameplay. In line with Skinner's [11] operant conditioning theory, biosignals are processed by data-driven algorithms to generate corresponding rewards or punishments in a computer-generated environment, such that effective regulation strategies would lead to successful advancements in the game. This human-computer interaction can encourage greater engagement as well as making the goals and feedback more accessible and intuitive for those without specialised knowledge [12]. Game-based interventions may also particularly appeal to young people who tend to be more visually oriented, enjoy dynamic interactions, and motivated by playful learning experiences in video games [1], [13].

With explicit access to a representation of their interoceptive signals, individuals are then prompted to monitor their ability to regulate otherwise-involuntary physiological processes. Ultimately, biofeedback may equip an individual with enhanced interoceptive awareness, which relates to the conscious perception of interoception, an umbrella term encompassing the process by which the nervous system senses, interprets, and integrates information concerning the state of inner body systems [14], [15]. For example, Meyerholz et al. [16] has shown that cardio-based feedback training can significantly improve cardioception, providing evidence for the trainability of heartbeat perception. This suggests one mechanism by which biofeedback training could contribute to improving physiological symptoms of

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mental health conditions. Moreover, interoception is associated with awareness of emotional states, which serves as a critical prerequisite for emotion regulation and decision making processes [17]. Thus, over time, successful implementation of biofeedback could influence mental states, improve psychological well-being, and encourage proactive physiological regulation without the external assistance of self-monitoring instruments.

While promising, few studies have examined the effect of game-based biofeedback on interoceptive awareness. Although interoception has been proposed as a cognitive mechanism underlying the effectiveness of biofeedback, the assumption that biofeedback could enhance conscious awareness of physiological states remains largely theoretical and lack empirical evidence. Past studies employing SPB training and biofeedback systems primarily focused on objective measurements of interoceptive behavioural performance (i.e., interoceptive accuracy and interoceptive sensitivity), which do not necessary associate with subjective, consciously experienced interoceptive features [18], [19]. Furthermore, limited literature explored the association of interoceptive awareness with two-dimensional and three-dimensional visualisation of physiological responses in biofeedback. This is an important gap in knowledge in terms of fully understanding the mechanisms underlying clinical benefits of biofeedback. Changes in interoceptive awareness could provide a valuable marker in assessing and comparing impact of different biofeedback approaches on self-regulation.

Using a subset of data from a larger project exploring the effect of biofeedback modalities on emotion regulation, the present study aims to explore the effectiveness of a novel biofeedback game co-developed by our research team and Ninja Theory Ltd in improving interoceptive awareness, and specifically, whether its impact might differ across virtual reality (VR) and flat screen (FS) modalities. The main hypotheses are as follows:

- Hypothesis 1: Game-based biofeedback facilitated through VR (H1a) and FS display (H1b) would elicit a significant improvement in all dimensions of interoceptive awareness.
- Hypothesis 2: When compared to FS biofeedback, VR biofeedback would elicit a greater improvement in all dimensions of interoceptive awareness.

II. Related Work

A. Technological Advancements in Biofeedback

Commonly used as a mind-body technique to regulate involuntary bodily processes, the application of biofeedback in healthcare settings ranges from anxiety reduction [20], [21], stress management [22], [23], asthma [24], to physical and neuromotor rehabilitation [25], [26], [27]. While biofeedback training has been largely conducted in two-dimensional FS environments with minimal narrative and, often, fairly rudimentary representation of physiological signals, technological advances in recent years offer new, and potentially more engaging, possibilities. VR has emerged to be a safe and engaging tool to render realistic immersion for therapeutic purposes [28]. The integration of VR systems into biofeedback is efficacious for a range of clinical outcomes, such as improving symptoms of generalised anxiety disorder [29], [30], reducing psychological stress [31], [32], fostering a positive stress mindset [33], and managing chronic pain [34], [35]. When compared to traditional FS approaches, VR can improve user experience and generalisability of biofeedback interventions by eliciting higher levels of motivation, involvement, and attentional focus [36], [37], [38]. However, few studies compared mental health outcomes across display modalities. In this study, we hypothesized that VR, which offers an immersive multisensory experience, would be a more effective medium than FS for developing interoceptive awareness.

Over the past decade, there has been growing interest in employing game-based learning approaches within biofeedback interventions to improve adolescent mental health [1], [39], [40]. Incorporating representations of real-time physiological signals into gameplay allows users to learn self-regulation skills in a personalised and interactive environment. Past research has demonstrated the efficacy of biofeedback games in enhancing attention-cognitive performance [41] as well as lowering HRV, a strong physiological marker of stress, under stress induction [31]. Notably, game-based biofeedback incorporating SPB training has been found to improve awareness of respiratory symptoms, breath control, and heart rate control associated with a strong sense of agency, all of which are factors potentially relevant to interoception [36], [39], [41], [42].

B. Interoceptive Awareness and Mental Health

Interoceptive processing occurs across major biological systems involved in supporting homeostatic control and allostatic adaptation. Few interoceptive processes occur in conscious awareness, yet subjective experiences influence emotion regulation in ways that might not be reflected by objective measures. In past studies, the construct of interoceptive awareness, here defined as consciously experienced interoceptive features, has been used interchangeably as interoceptive sensibility and commonly examined using self-report measures [15], [43], [44], [45]. However, it is important to note that some literature consider these as separate entities and operationalised interoceptive awareness as the metacognitive correspondence between subjective and objective measures of interoception [1]. In order to estimate changes in interoceptive awareness elicited by VR and FS biofeedback games, we used the youth version of Multidimensional Assessment of Interoceptive Awareness [46] to investigate how people notice, experience and discriminate interoceptive signals.

As posited by the James-Lange theory of emotion, interoception is fundamental to the formation and experience of emotions [47]. The somatic marker hypothesis indicates that interoceptive awareness plays a pivotal role in emotional processing as well as cognition relating to decision-making and attention [48], [49]. These theoretical frameworks are well supported by empirical research in neuroscience. For instance, Pollatos et al. [50] showed that the perception of cardiac signals is significantly associated with cortical processing of emotional stimuli, indicating a strong relationship between interoceptive awareness and emotion-related brain activity. In addition, Terasawa et al.'s [51] functional magnetic resonance imaging (fMRI) study examining neural activity found that subjective evaluation of interoceptive state is critical for the awareness of emotional state.

Importantly, recent studies have shown potential neuroplasticity effects of interoceptive awareness, indicating that the capacity to sense and appraise bodily signals can potentially be improved through practice [52]. As suggested

by Mather and Thayer [53], increasing the amplitude of HRV through self-regulation processes, such as biofeedback, could lead to better emotional regulation and interoceptive processing through stimulating synchrony in cerebral blood flow and enhancing functional connectivity in brain networks. This association is supported by a recent systematic review [54], which further demonstrated higher interoception to be predictive of effective downregulation of negative emotions. This has important implications for emotion regulation, which involves the ability to effectively appraise physiological reactions and maintain coherent body-mind communications [55]. Given that adolescence, a period of rapid cognitive, physiological, and psychosocial development, is associated with higher vulnerability to adversity and likelihood for onset of mental disorders, effective strategies for improving interoceptive awareness and emotion regulation is therefore central to adolescent mental health [56].

III. Methods

A. Participants

45 healthy adolescent volunteers with a mean age of 17.3 years (range: 16–18, SD = 0.78 years) participated in the biofeedback experiment between November and December 2023. Participants were recruited via convenient sampling using online advertisements, posters, and institutional mass-mailing in Cambridgeshire. 60% of the participants (n = 27) self-identified as female, 35.6% (n = 16) as male, and 4.4% (n = 2) as non-binary. Eligible participants should have normal or corrected-to-normal vision and adequate stereopsis. Exclusion criteria included any significant history of cardiovascular, neurological, metabolic, or psychiatric illness, recent use of medication affecting cardiovascular function, alcohol or substance misuse in the past six months, smoking, and pregnancy. Ethical approval for this study was obtained from Cambridge Psychology Research Ethics Committee.

B. Game-based Biofeedback

In this study, we developed a novel biofeedback game to encourage physiological regulation and examine interoceptive awareness. Participants were invited to play an identical biofeedback game from a first-person perspective using two modalities (i.e., VR or FS) in a randomized order. The game scenario (see Figure 1), set in a calm sea during sunset, was designed for participants to learn and practice physiological regulation through SPB in a relaxing and intuitive manner.

The game experience and biometrics of participants were monitored by researchers via a designated software interface (Figure 2). In the game, participants were positioned on a virtual boat and asked to optimise its movement by lowering their breathing rate and heart rate. Specifically, they were instructed to inhale, hold their breath, and exhale at regular 5-second intervals for a predetermined set of breathing cycles. The SPB instructions were delivered via audiovisual cues in the virtual environment. Instructions for each phase of the breathing cycle (e.g., ‘breathe in’, ‘hold’, and ‘breathe out’) were presented in the middle of the screen and pronounced in a neutral tone. In addition, the guided breathing pattern was indicated by movements of light particles in the sky, which would expand and retract during the inhalation phase and exhalation phase, respectively, in order to assist participants in learning SPB techniques.



Fig. 1. Example still of the virtual environment in the biofeedback game



Fig. 2. User interface of biofeedback game software

As part of the biofeedback mechanism (Figure 3), participants were told that their heart rate was measured and programmed to positively correlate with the boat propulsion. In other words, their performance was indicated by the speed of the boat, such that those with higher effectiveness in learning and applying SPB techniques would steer the boat and reach the finish line at a faster rate (range: 3.5–7 minutes). In addition, their pulse wave (a direct readout of their digital photoplethysmogram) was displayed on the prow of the boat for participants to monitor their real-time biofeedback performance. In summary, the biofeedback game measures, translates, and integrates biosignals into game mechanics in order to feedback useful physiological information for participants to monitor and learn self-regulation skills in a close-loop system.

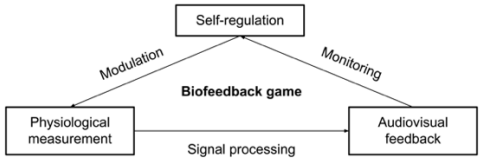


Fig. 3. The mechanism of biofeedback games



Fig. 4. Set-up of the biofeedback game

C. Apparatus

A digital pulse oximeter was used for taking photoplethysmography (PPG) readings at baseline and during the biofeedback intervention. The PPG signals were acquired by Great Lakes NeuroTechnologies BioRadio™ and streamed to BioCapture™ data acquisition system via Bluetooth for signal processing and real-time monitoring on a desktop computer interface. Heart rate data was extracted from PPG recordings then further incorporated into the biofeedback game, which was co-designed and operated using custom software from Ninja Theory Ltd. The games were programmed and run from a Windows 10 PC with an Intel® Core™ i9-9900K CPU @ 3.60 Ghz processor, 64 GB Ram. Stimulus delivery was facilitated by an HTC Vive Pro Eye head-mounted display (HMD) with inbuilt headphones. Figure 4 illustrates the game set-up.

D. Measures

The 32-item Multidimensional Assessment of Interoceptive Awareness (MAIA) – Youth Version [46] is a well-validated self-report interoception measure adapted from MAIA [15], [45] for younger respondents. It was used to assess five overarching dimensions of interoceptive awareness, including: (1) awareness of body sensations, (2) emotion reaction and attentional response to sensations, (3) capacity to regulate attention, (4) trusting body sensations, and (5) mind-body integration. It consists of eight subscales: the 4-item Noticing subscale (i.e., awareness of uncomfortable, comfortable, or neutral body sensations), 3-item Not Distracting subscale (i.e., tendency not to use distraction to cope with discomfort), 3-item Not Worrying subscale (i.e., tendency not to experience emotional distress with physical discomfort), 7-item Attention Regulation subscale (i.e., ability to sustain and control attention to body sensations), 3-item Trusting subscale (i.e., experience of one's body as safe and trustworthy), 5-item Emotional Awareness subscale (i.e., ability to attribute specific physical sensations to physiological manifestations of emotions), 4-item Self-Regulation subscale (i.e., ability to regulate distress by attention to body sensations), and 3-item Body Listening subscale (i.e., tendency to actively listen to the body for insight). All items were rated on a 6-point scale ranging from 0 (never) to 5 (always), with negative items being reversed scored, then averaged to produce a final score for each subscale. Higher scores indicated a higher level of interoceptive awareness.

E. Procedure

Eligible participants were invited to attend a one-hour experimental session in a VR laboratory at the Department of Psychiatry, University of Cambridge. Participants were briefed in advance about the biofeedback game and were asked to experience two display modalities (i.e., VR condition and FS condition) in a randomised order. Upon arrival, participants provided written informed consent and completed baseline MAIA measures. Participants also provided information relating to demographics and emotion regulation, but these will not be discussed within the scope of this study. A digital pulse oximeter was placed on the index finger of their non-dominant hand and PPG recordings were acquired throughout the intervention, including a 5-minute baseline taken in a relaxed state before each of the two biofeedback games. In the VR condition, participants were assisted in wearing an HMD to facilitate both the baseline measurement and biofeedback game in an immersive environment. This was arranged to ensure that participants had adequate time to adapt to the virtual environment and for minimising the novelty effect of VR in the game experience. Participants were asked to remain seated throughout the game in order to minimise noise in physiological recordings and effects of cybersickness. Participants filled in a post-game MAIA questionnaire after completing the VR condition and FS condition, respectively.

F. Data Analysis

Statistical analyses of self-reported measures were conducted from 45 participants. There were no data exclusions. The primary analysis examined the effectiveness of game-based biofeedback in improving interoceptive awareness and compared its impact across two targeted modalities, VR biofeedback and FS biofeedback. Linear mixed model analyses were performed by assessing main effects and interaction of group (VR biofeedback and FS biofeedback) and time (order of conditions) for interoceptive awareness. The model fit was assessed using restricted maximum likelihood (REML) estimation. Bonferroni correction was applied to account for multiple comparisons.

IV. Results

A. Hypothesis 1: Game-based Biofeedback and Interoceptive Awareness

Table 1 summarises the analysis results of H1a and H1b, which examine the effect of VR biofeedback and FS bifoeedback on interoceptive awareness, respectively.

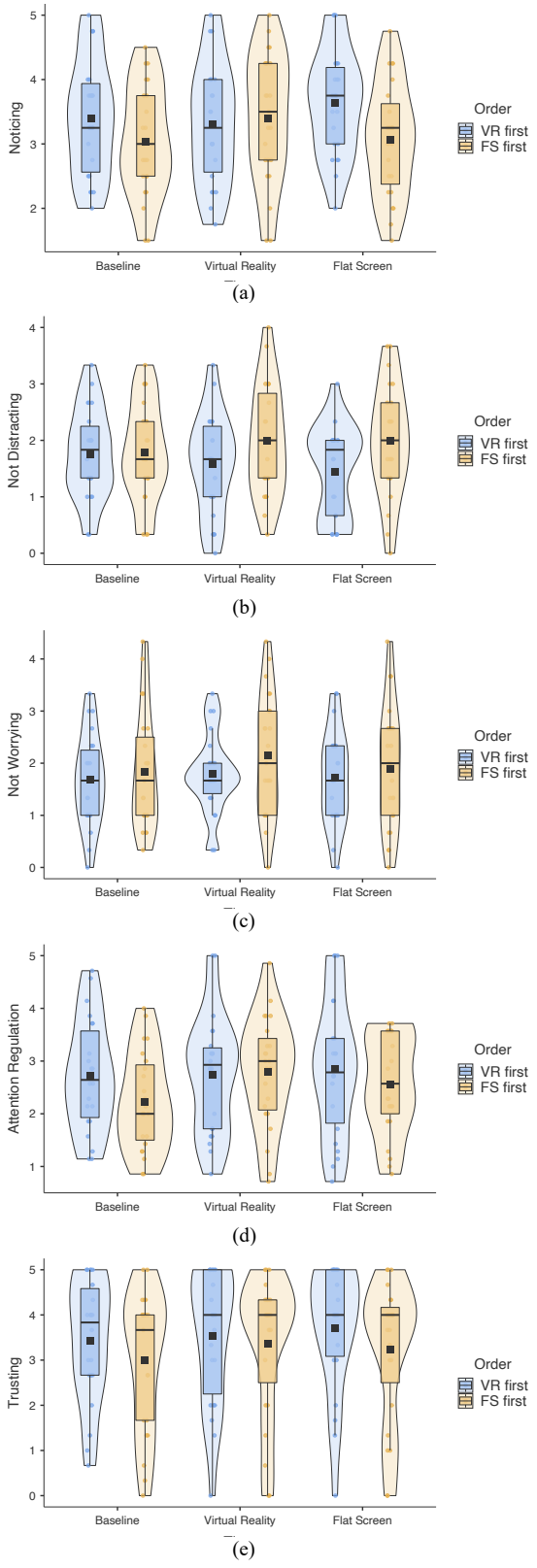
Compared to baseline, VR biofeedback elicited a significant increase in self-reported capacity to regulate attention and trusting body sensations, as indicated by *Attention Regulation* and *Trusting* subscales, respectively. A significant increase in mind-body integration was shown in *Emotional Awareness*, *Self-Regulation*, and *Body Listening* subscales. The improvement in *Not Worrying* subscale did not survive Bonferroni correction. No significant improvement was observed in *Noticing* and *Not Distracting* subscales.

TABLE I. SUMMARY OF MAIA SUBSCALES IN VR BIOFEEDBACK

MAIA	*Modality*	*b*	*SE*	*t*	*p*
Attention Regulation	VR	0.30	0.11	2.65	0.029
	FS	0.22	0.11	1.97	0.16
Trusting	VR	0.24	0.091	2.65	0.029
	FS	0.26	0.091	2.85	0.017
Emotional Awareness	VR	0.45	0.096	4.67	<.001
	FS	0.40	0.096	4.15	<.001
Self-Regulation	VR	0.71	0.12	6.77	<.001
	FS	0.64	0.11	6.10	<.001
Body Listening	VR	0.53	0.11	4.91	<.001
	FS	0.58	0.11	5.41	<.001
Not Worrying	VR	0.21	0.09	2.28	0.075
	FS	0.052	0.09	0.58	1.00
Noticing	VR	0.14	0.089	1.57	0.36
	FS	0.14	0.089	1.52	0.39
Not Distracting	VR	0.018	0.094	0.19	1.00
	FS	-0.050	0.094	-0.54	1.00

Compared to baseline, FS biofeedback elicited a significant increase in trusting body sensations, as indicated by the *Trusting* subscale. A significant increase in mind-body integration was shown in *Emotional Awareness*, *Self-Regulation*, and *Body Listening* subscales. No significant improvement was observed in *Noticing*, *Not Distracting*, *Not Worrying*, and *Attention Regulation* subscales.

Figure 5 summarises the descriptive statistics of all MAIA subscales at baseline and biofeedback.



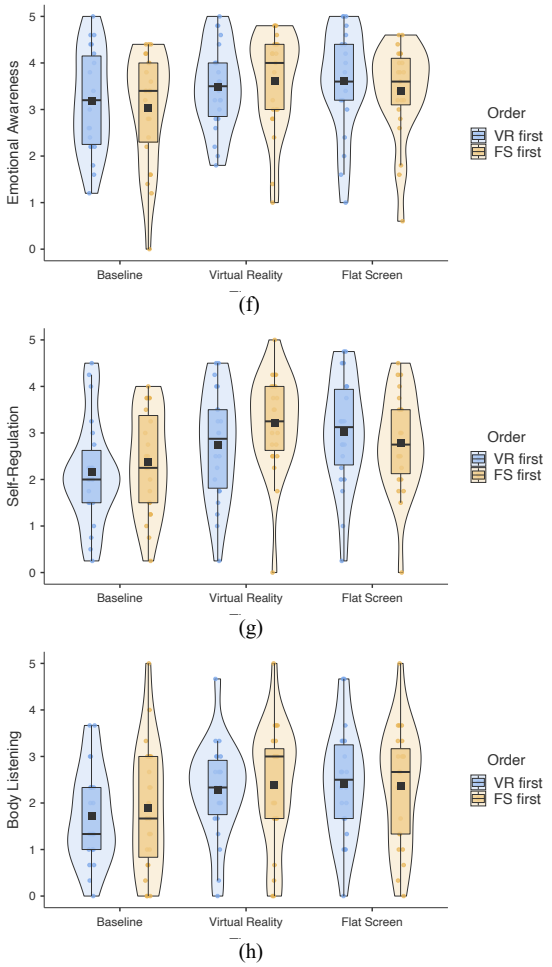


Fig. 5. Box plots illustrating the mean, median, interquartile range, data points of different dimensions of interoceptive awareness at baseline, virtual reality biofeedback, and flat screen biofeedback. Interoceptive awareness was measured by MAIA scales: Noticing (a), Not Distracting (b), Not Worrying (c), Attention Regulation (d), Trusting (e), Emotion Awareness (f), Self-Regulation (g), and Body Listening (h).

B. Hypothesis 2: A Comparison Between Virtual Reality Biofeedback and Flat Screen Biofeedback

No significant difference was found between VR and FS biofeedback conditions in all dimensions of interoception.

As an exploratory analysis, the interaction effect between modality and order was examined. The interaction of VR biofeedback and order was significant in the *Noticing* subscale ($b = 0.46$, SE = 0.18, $t(86) = 2.59$, $p = 0.011$), *Not Distracting* subscale ($b = 0.40$, SE = 0.19, $t(86) = 2.12$, $p = 0.037$), and *Attention Regulation* subscale ($b = 0.54$, SE = 0.22, $t(86) = 2.41$, $p = 0.018$), indicating that the order of experimental conditions (i.e., experiencing VR biofeedback after prior exposure to FS biofeedback) influenced the effect of VR biofeedback in increasing self-reported awareness of body sensations, attentional response to sensations, and capacity to regulate attention, respectively. The interaction of FS biofeedback and order was significant in the *Not Distracting* subscale ($b = 0.54$, SE = 0.19, $t(86) = 2.85$, $p = 0.006$) and *Self-Regulation* subscale ($b = -0.43$, SE = 0.21, $t(86) = -2.05$, $p = 0.044$), indicating that the order of experimental conditions (i.e., experiencing FS biofeedback after prior exposure to VR biofeedback) influenced the effect of FS biofeedback in increasing attentional response to sensations and the ability to regulate distress by attention to body sensations, respectively.

V. Discussion

The present study investigated the impact of a novel biofeedback game on interoceptive awareness, as measured by MAIA. Consistent with Hypothesis 1, both VR and FS modalities of game-based biofeedback elicited significant increases in beliefs concerning the importance of sensations (Trusting) and in facets of embodied self-awareness (Emotional Awareness, Self-Regulation, and Body Listening) relative to baseline. Experiencing the biofeedback game for 3.5 to 7 minutes increased the self-reported ability to detect and perceive bodily responses, regardless of valence (i.e., positive, negative, or neutral), as useful for making informed decisions to improve physical and mental health. Moreover, an enhanced awareness that physical sensations form the sensory foundation of emotions can empower individuals to regulate their physiological states in order to better manage their emotional states. Indeed, past studies have demonstrated positive associations of interoceptive awareness with the recognition, regulation, and experience of emotions [17], [57], [58], [59]. The dynamic interplay between human-computer interaction and interoceptive processes evidenced in this study highlights the capacity of biofeedback games to cultivate a more cohesive integration of mental, emotional, and physiological processes. These findings align with prior research demonstrating the efficacy of traditional biofeedback methods in enhancing interoception, providing empirical evidence for theoretical mechanisms associating biofeedback with improvements in conscious awareness of physiological states [16], [60]. Nevertheless, the findings are limited by self-report, which can be susceptible to socially desirable responding. As interoceptive awareness do not necessary associate with interoceptive accuracy, future research can employ and examine correlations between subjective ratings of interoceptive awareness and objective measures of interoceptive behavioural performance in biofeedback.

Interestingly, game-based biofeedback facilitated by VR, but not FS, conferred an added potential benefit of improving attention regulation, which refers to the ability to sustain and control attention on bodily sensations amidst competing sensory stimuli. It is possible that the immersive and multisensory nature of VR underpins this active regulatory process. Based on Barbe et al.'s [61] visual-auditory-kinaesthetic learning styles model, VR technology supports immersive learning via multiple perceptual modalities simultaneously, which enhances user engagement and motivation for improved educational, behavioural, and psychological outcomes when compared to traditional methods [62], [63], [64]. In comparison to traditional controlled interface for gaming (such as controllers and keyboards), integrating breath control in the game-based learning process can enhance a sense of realism and presence in human-computer interactions [10], [65]. Notably, natural sensorimotor contingencies, which are often provided through direct interactions with the environment, are essential for facilitating a sense of agency in VR [66], [67]. In the context of this study, the VR biofeedback game immersed participants in a dynamic environment that reflects real-time changes of their physiological responses, such that their biosignals became part of their surrounding environment, rather than graphics presented on a flat screen. The alignment in SPB and resulting multisensory feedback from the virtual environment might have enhanced the naturalness of the virtual experience, fostering a higher level of engagement and attention to one's interoceptive signals.

Contrary to Hypothesis 2, VR and FS biofeedback did not differ in their impact on interoceptive awareness, indicating that both modalities are favourable for learning self-regulation skills in game-based biofeedback. However, exploratory analyses revealed that the order in which VR and FS biofeedback were experienced influenced specific interoceptive outcomes in self-regulation, as well as the awareness of bodily sensations and attentional responses—dimensions that neither modality significantly improved when examined independently. While VR has proven to be a promising medium for facilitating biofeedback interventions, it is essential to account for individual differences that may limit its efficacy and generalisability. Cybersickness–characterised by symptoms such as nausea and dizziness–and varying levels of adaptability to the novelty of immersive technology can influence user engagement and the broader applicability of VR interventions [68], [69]. As a result, some individuals might prefer 2-D FS experiences, which, while less immersive, still offer substantial benefits. These findings suggest that multiple sessions may be necessary to optimise the effects of biofeedback on interoceptive awareness. Future research can measure cybersickness in VR biofeedback and employ a longitudinal experiment design to investigate the long-term efficacy of game-based biofeedback interventions.

Through enhancing the awareness of one's physiological responses, breath control biofeedback games offer a promising approach to guide favourable behavioural change for emotion regulation, and ultimately, sustainable improvement in well-being. The present study demonstrates that game technology, immersive technology, and wearable sensor technology can be capitalised to create enjoyable and personalised biofeedback interventions for adolescents, individuals who perceive emotion as abstract and challenging to regulate, and those who might otherwise find traditional treatments unappealing. Game-based biofeedback is a cost-effective approach that could be highly transferable and accessible to school settings, remote therapeutic use, and clinical populations. These findings may prove informative for researchers aiming to improve interoceptive awareness using VF and FS biofeedback games and demonstrates the potential of game-based interventions in improving community mental health with state-of-the-art technology.

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References

[1] M. Knox, J. Lentini, T. S. Cummings, A. McGrady, K. Whearty, and L. Sancrant, "Game-based biofeedback for paediatric anxiety and depression," *Ment. Health Fam. Med.*, vol. 8, no. 3, pp. 195–203, 2011.

[2] M. Van Rooij, A. Lobel, O. Harris, N. Smit, and I. Granic, "DEEP: A Biofeedback Virtual Reality Game for Children At-risk for Anxiety," in *Proceedings of the 2016 CHI Conference Extended Abstracts on*

Human Factors in Computing Systems, San Jose California USA: ACM, May 2016, pp. 1989–1997. doi: 10.1145/2851581.2892452.

[3] R. McCraty and R. T. Bradley, "The Coherent Heart Heart–Brain Interactions, Psychophysiological Coherence, and the Emergence of System-Wide Order," vol. 5, no. 2, 2009.

[4] R. McCraty and M. A. Zayas, "Cardiac coherence, self-regulation, autonomic stability, and psychosocial well-being," *Front. Psychol.*, vol. 5, Sep. 2014, doi: 10.3389/fpsyg.2014.01090.

[5] C. Sevoz-Couche and S. Laborde, "Heart rate variability and slow-paced breathing:when coherence meets resonance," *Neuroscience & Biobehavioral Reviews*, vol. 135, p. 104576, Apr. 2022, doi: 10.1016/j.neubiorev.2022.104576.

[6] F. C. M. Geisler, T. Kubiak, K. Siewert, and H. Weber, "Cardiac vagal tone is associated with social engagement and self-regulation," *Biological Psychology*, vol. 93, no. 2, pp. 279–286, May 2013, doi: 10.1016/j.biopsycho.2013.02.013.

[7] S. Laborde, E. Mosley, and J. F. Thayer, "Heart Rate Variability and Cardiac Vagal Tone in Psychophysiological Research – Recommendations for Experiment Planning, Data Analysis, and Data Reporting," *Front. Psychol.*, vol. 8, Feb. 2017, doi: 10.3389/fpsyg.2017.00213.

[8] R. Mccraty and F. Shaffer, "Heart Rate Variability: New Perspectives on Physiological Mechanisms, Assessment of Self-regulatory Capacity, and Health Risk," *Glob Adv Health Med*, vol. 4, no. 1, pp. 46–61, Jan. 2015, doi: 10.7453/gahmj.2014.073.

[9] M. Leganes-Fonteneau *et al.*, "Cardiovascular mechanisms of interoceptive awareness: Effects of resonance breathing," *International Journal of Psychophysiology*, vol. 169, pp. 71–87, Nov. 2021, doi: 10.1016/j.ijpsycho.2021.09.003.

[10] L. E. Nacke, M. Kalyn, C. Lough, and R. L. Mandryk, "Biofeedback game design: using direct and indirect physiological control to enhance game interaction," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, Vancouver BC Canada: ACM, May 2011, pp. 103–112. doi: 10.1145/1978942.1978958.

[11] B. F. Skinner, "Two Types of Conditioned Reflex: A Reply to Konorski and Miller," *The Journal of General Psychology*, Jan. 1937.

[12] A. Lobel, M. Gotsis, E. Reynolds, M. Annetta, R. C. M. E. Engels, and I. Granic, "Designing and Utilizing Biofeedback Games for Emotion Regulation: The Case of Nevermind," in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, in CHI EA '16. New York, NY, USA: Association for Computing Machinery, May 2016, pp. 1945–1951. doi: 10.1145/2851581.2892521.

[13] K. Martinez, M. I. Menéndez-Menéndez, and A. Bustillo, "Awareness, Prevention, Detection, and Therapy Applications for Depression and Anxiety in Serious Games for Children and Adolescents: Systematic Review," *JMIR Serious Games*, vol. 9, no. 4, p. e30482, Dec. 2021, doi: 10.2196/30482.

[14] A. (Bud) Craig, "Interoception: the sense of the physiological condition of the body," *Current Opinion in Neurobiology*, vol. 13, no. 4, pp. 500–505, Aug. 2003, doi: 10.1016/S0959-4388(03)00090-4.

[15] W. E. Mehling, C. Price, J. J. Daubenmier, M. Acree, E. Bartmess, and A. Stewart, "The Multidimensional Assessment of Interoceptive Awareness (MAIA)," *PLOS ONE*, vol. 7, no. 11, p. e48230, Nov. 2012, doi: 10.1371/journal.pone.0048230.

[16] L. Meyerholz, J. Irzinger, M. Witthöft, A. L. Gerlach, and A. Pohl, "Contingent biofeedback outperforms other methods to enhance the accuracy of cardiac interoception: A comparison of short interventions," *Journal of Behavior Therapy and Experimental Psychiatry*, vol. 63, pp. 12–20, Jun. 2019, doi: 10.1016/j.jbtep.2018.12.002.

[17] J. Füstös, K. Gramann, B. M. Herbert, and O. Pollatos, "On the embodiment of emotion regulation: interoceptive awareness facilitates reappraisal," *Social Cognitive and Affective Neuroscience*, vol. 8, no. 8, pp. 911–917, Dec. 2013, doi: 10.1093/scan/nss089.

[18] S. N. Garfinkel, A. K. Seth, A. B. Barrett, K. Suzuki, and H. D. Critchley, "Knowing your own heart: Distinguishing interoceptive accuracy from interoceptive awareness," *Biological Psychology*, vol. 104, pp. 65–74, Jan. 2015, doi: 10.1016/j.biopsycho.2014.11.004.

[19] C. Rominger and A. R. Schwerdtfeger, "The misjudgment of interoceptive awareness: Systematic overrating of interoceptive awareness among individuals with lower interoceptive metacognitive skills," *Consciousness and Cognition*, vol. 117, p. 103621, Jan. 2024, doi: 10.1016/j.concog.2023.103621.

[20] M. Alneyadi, N. Drissi, M. Almeqbaali, and S. Ouhbi, "Biofeedback-Based Connected Mental Health Interventions for Anxiety: Systematic Literature Review," *JMIR mHealth and uHealth*, vol. 9, no. 4, p. e26038, Apr. 2021, doi: 10.2196/26038.

[21] V. C. Goessl, J. E. Curtiss, and S. G. Hofmann, "The effect of heart rate variability biofeedback training on stress and anxiety: a meta-analysis," *Psychological Medicine*, vol. 47, no. 15, pp. 2578–2586, Nov. 2017, doi: 10.1017/S0033291717001003.

[22] L. Kennedy and S. H. Parker, "Biofeedback as a stress management tool: a systematic review," *Cogn Tech Work*, vol. 21, no. 2, pp. 161–190, May 2019, doi: 10.1007/s10111-018-0487-x.

[23] B. Yu, M. Funk, J. Hu, Q. Wang, and L. Feijs, "Biofeedback for Everyday Stress Management: A Systematic Review," *Frontiers in ICT*, vol. 5, 2018.

[24] P. M. Lehrer *et al.*, "Biofeedback Treatment for Asthma," *Chest*, vol. 126, no. 2, pp. 352–361, Aug. 2004, doi: 10.1378/chest.126.2.352.

[25] O. M. Giggins, U. M. Persson, and B. Caulfield, "Biofeedback in rehabilitation," *J NeuroEngineering Rehabil*, vol. 10, no. 1, Art. no. 1, Dec. 2013, doi: 10.1186/1743-0003-10-60.

[26] H. Huang, S. L. Wolf, and J. He, "Recent developments in biofeedback for neuromotor rehabilitation," *J NeuroEngineering Rehabil*, vol. 3, no. 1, p. 11, Dec. 2006, doi: 10.1186/1743-0003-3-11.

[27] K. Nakamura, N. Toda, K. Sakamaki, K. Kashima, and N. Takeda, "Biofeedback Rehabilitation for Prevention of Synkinesis after Facial Palsy," *Otolaryngol Head Neck Surg*, vol. 128, no. 4, pp. 539–543, Apr. 2003, doi: 10.1016/S0194-59980223254-4.

[28] S. F. Kuliga, T. Thrash, R. C. Dalton, and C. Hölscher, "Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model," *Computers, Environment and Urban Systems*, vol. 54, pp. 363–375, Nov. 2015, doi: 10.1016/j.compenvurbsys.2015.09.006.

[29] F. Pallavicini, D. Algeri, C. Repetto, A. Gorini, and G. Riva, "Biofeedback virtual reality and mobile phones in the treatment of generalized anxiety disorder (GAD): a phase-2 controlled clinical trial," *Journal of Cyber Therapy and Rehabilitation*, vol. 2, pp. 315–327, Jan. 2009.

[30] C. Repetto, A. Gaggioli, F. Pallavicini, P. Cipresso, S. Raspelli, and G. Riva, "Virtual reality and mobile phones in the treatment of generalized anxiety disorders: a phase-2 clinical trial," *Pers Ubiquit Comput*, vol. 17, no. 2, pp. 253–260, Feb. 2013, doi: 10.1007/s00779-011-0467-0.

[31] L. Daniel-Watanabe *et al.*, "Using a virtual reality game to train biofeedback-based regulation under stress conditions," *Psychophysiology*, p. e14705, doi: 10.1111/psyp.14705.

[32] A. Gaggioli *et al.*, "Experiential Virtual Scenarios With Real-Time Monitoring (Interreality) for the Management of Psychological Stress: A Block Randomized Controlled Trial," *Journal of Medical Internet Research*, vol. 16, no. 7, p. e3235, Jul. 2014, doi: 10.2196/jmir.3235.

[33] B. M. Maarsingh, J. Bos, C. F. J. Van Tuijn, and S. B. Renard, "Changing Stress Mindset Through Stressjam: A Virtual Reality Game Using Biofeedback," *Games for Health Journal*, vol. 8, no. 5, pp. 326–331, Oct. 2019, doi: 10.1089/g4h.2018.0145.

[34] S. Shiri *et al.*, "A Virtual Reality System Combined with Biofeedback for Treating Pediatric Chronic Headache—A Pilot Study," *Pain Med*, vol. 14, no. 5, pp. 621–627, May 2013, doi: 10.1111/pme.12083.

[35] X. Tong, D. Gromala, A. Choo, A. Amin, and C. Shaw, "The Virtual Meditative Walk: An Immersive Virtual Environment for Pain Self-modulation Through Mindfulness-Based Stress Reduction Meditation," in *Virtual, Augmented and Mixed Reality*, Springer, Cham, 2015, pp. 388–397. doi: 10.1007/978-3-319-21067-4_40.

[36] J. Blum, C. Rockstroh, and A. S. Göritz, "Heart Rate Variability Biofeedback Based on Slow-Paced Breathing With Immersive Virtual Reality Nature Scenery," *Frontiers in Psychology*, vol. 10, 2019.

[37] T. Kojić, L. T. Nugyen, and J.-N. Voigt-Antons, "Impact of Constant Visual Biofeedback on User Experience in Virtual Reality Exergames," in *2019 IEEE International Symposium on Multimedia (ISM)*, Dec. 2019, pp. 307–3073. doi: 10.1109/ISM46123.2019.00068.

[38] C. Rockstroh, J. Blum, and A. S. Göritz, "Virtual reality in the application of heart rate variability biofeedback," *International Journal of Human-Computer Studies*, vol. 130, pp. 209–220, Oct. 2019, doi: 10.1016/j.ijhcs.2019.06.011.

[39] P. M. Bingham, J. H. T. Bates, J. Thompson-Figueroa, and T. Lahiri, "A Breath Biofeedback Computer Game for Children With Cystic Fibrosis," *Clin Pediatr (Phila)*, vol. 49, no. 4, pp. 337–342, Apr. 2010, doi: 10.1177/0009922809348022.

[40] N. Pop-Jordanova and Z. Gucev, "Game-based peripheral biofeedback for stress assessment in children," *Pediatrics International*, vol. 52, no. 3, pp. 428–431, 2010, doi: 10.1111/j.1442-200X.2009.02978.x.

[41] M. A. Zafar, B. Ahmed, R. A. Rihawi, and R. Gutierrez-Osuna, "Gaming Away Stress: Using Biofeedback Games to Learn Paced Breathing," *IEEE Transactions on Affective Computing*, vol. 11, no. 3, pp. 519–531, Jul. 2020, doi: 10.1109/TAFFC.2018.2816945.

[42] S. Houzangbe, O. Christmann, G. Gorisse, and S. Richir, "Effects of voluntary heart rate control on user engagement and agency in a virtual reality game," *Virtual Reality*, vol. 24, no. 4, pp. 665–681, Dec. 2020, doi: 10.1007/s10055-020-00429-7.

[43] N. Farb *et al.*, "Interoception, contemplative practice, and health," *Front. Psychol.*, vol. 6, Jun. 2015, doi: 10.3389/fpsyg.2015.00763.

[44] S. S. Khalsa *et al.*, "Interoception and Mental Health: A Roadmap," *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, vol. 3, no. 6, pp. 501–513, Jun. 2018, doi: 10.1016/j.bpsc.2017.12.004.

[45] W. E. Mehling, M. Acree, A. Stewart, J. Silas, and A. Jones, "The Multidimensional Assessment of Interoceptive Awareness, Version 2 (MAIA-2)," *PLoS ONE*, vol. 13, no. 12, p. e0208034, Dec. 2018, doi: 10.1371/journal.pone.0208034.

[46] A. Jones *et al.*, "Exploring the Multidimensional Assessment of Interoceptive Awareness in youth aged 7–17 years," *Journal of Clinical Psychology*, vol. 77, no. 3, pp. 661–682, Mar. 2021, doi: 10.1002/jclp.23067.

[47] W. B. Cannon, "The James-Lange Theory of Emotions: A Critical Examination and an Alternative Theory," *The American Journal of Psychology*, vol. 39, no. 1/4, pp. 106–124, 1927, doi: 10.2307/1415404.

[48] A. D. (Bud) Craig, "Human feelings: why are some more aware than others?," *Trends in Cognitive Sciences*, vol. 8, no. 6, pp. 239–241, Jun. 2004, doi: 10.1016/j.tics.2004.04.004.

[49] A. R. Damasio, "The somatic marker hypothesis and the possible functions of the prefrontal cortex," *Philos Trans R Soc Lond B Biol Sci*, vol. 351, no. 1346, pp. 1413–1420, Oct. 1996, doi: 10.1098/rstb.1996.0125.

[50] O. Pollatos, W. Kirsch, and R. Schandry, "On the relationship between interoceptive awareness, emotional experience, and brain processes," *Cognitive Brain Research*, vol. 25, no. 3, pp. 948–962, Dec. 2005, doi: 10.1016/j.cogbrainres.2005.09.019.

[51] Y. Terasawa, H. Fukushima, and S. Umeda, "How does interoceptive awareness interact with the subjective experience of emotion? An fMRI Study," *Human Brain Mapping*, vol. 34, no. 3, pp. 598–612, Mar. 2013, doi: 10.1002/hbm.21458.

[52] J. Gibson, "Mindfulness, Interoception, and the Body: A Contemporary Perspective," *Front. Psychol.*, vol. 10, Sep. 2019, doi: 10.3389/fpsyg.2019.02012.

[53] M. Mather and J. F. Thayer, "How heart rate variability affects emotion regulation brain networks," *Current Opinion in Behavioral Sciences*, vol. 19, pp. 98–104, Feb. 2018, doi: 10.1016/j.cobeha.2017.12.017.

[54] D. J. Edwards and T. Pinna, "A Systematic Review of Associations Between Interoception, Vagal Tone, and Emotional Regulation: Potential Applications for Mental Health, Wellbeing, Psychological Flexibility, and Chronic Conditions," *Front. Psychol.*, vol. 11, Aug. 2020, doi: 10.3389/fpsyg.2020.01792.

[55] C. J. Price and C. Hooven, "Interoceptive Awareness Skills for Emotion Regulation: Theory and Approach of Mindful Awareness in Body-Oriented Therapy (MABT)," *Front Psychol*, vol. 9, p. 798, May 2018, doi: 10.3389/fpsyg.2018.00798.

[56] N. A. J. D. Witte, S. Sütterlin, C. Braet, and S. C. Mueller, "Getting to the Heart of Emotion Regulation in Youth: The Role of Interoceptive Sensitivity, Heart Rate Variability, and Parental Psychopathology," *PLOS ONE*, vol. 11, no. 10, p. e0164615, Oct. 2016, doi: 10.1371/journal.pone.0164615.

[57] J. A. Sze, A. Gyurak, J. W. Yuan, and R. W. Levenson, "Coherence between emotional experience and physiology: does body awareness training have an impact," *Emotion*, vol. 10, no. 6, pp. 803–814, Dec. 2010, doi: 10.1037/a0020146.

[58] S. Wiens, "Interoception in emotional experience," *Current Opinion in Neurology*, vol. 18, no. 4, p. 442, Aug. 2005, doi: 10.1097/01.wco.0000168079.92106.99.

[59] G. Zamariola, N. Frost, A. Van Oost, O. Corneille, and O. Luminet, "Relationship between interoception and emotion regulation: New evidence from mixed methods," *Journal of Affective Disorders*, vol. 246, pp. 480–485, Mar. 2019, doi: 10.1016/j.jad.2018.12.101.

[60] J. Blascovich and W. B. Mendes, "Social Psychophysiology and Embodiment," in *Handbook of Social Psychology*, 1st ed., S. T. Fiske, D. T. Gilbert, and G. Lindzey, Eds., Wiley, 2010. doi: 10.1002/9780470561119.socpsy001006.

[61] W. B. Barbe, R. H. Swassing, and M. N. Milone, *Teaching through modality strengths : concepts and practices*. Zaner-Bloser, 1979.

[62] D. Allcoat and A. von Mühlenen, "Learning in virtual reality: Effects on performance, emotion and engagement," *Research in Learning Technology*, vol. 26, Nov. 2018, doi: 10.25304/rlt.v26.2140.

[63] W. Huang, R. D. Roscoe, M. C. Johnson-Glenberg, and S. D. Craig, "Motivation, engagement, and performance across multiple virtual reality sessions and levels of immersion," *Journal of Computer Assisted Learning*, vol. 37, no. 3, pp. 745–758, 2021, doi: 10.1111/jcal.12520.

[64] B. Mouatt, A. E. Smith, M. L. Mellow, G. Parfitt, R. T. Smith, and T. R. Stanton, "The Use of Virtual Reality to Influence Motivation, Affect, Enjoyment, and Engagement During Exercise: A Scoping Review," *Frontiers in Virtual Reality*, vol. 1, 2020.

[65] M. Sra, X. Xu, and P. Maes, "BreathVR: Leveraging Breathing as a Directly Controlled Interface for Virtual Reality Games," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, Montreal QC Canada: ACM, Apr. 2018, pp. 1–12. doi: 10.1145/3173574.3173914.

[66] K. Kilteni, R. Groten, and M. Slater, "The Sense of Embodiment in Virtual Reality," *Presence: Teleoperators and Virtual Environments*, vol. 21, no. 4, pp. 373–387, Nov. 2012, doi: 10.1162/PRES_a_00124.

[67] D. Perez-Marcos, "Virtual reality experiences, embodiment, videogames and their dimensions in neurorehabilitation," *J NeuroEngineering Rehabil*, vol. 15, no. 1, Art. no. 1, Dec. 2018, doi: 10.1186/s12984-018-0461-0.

[68] S. Davis, K. Nesbitt, and E. Nalivaiko, "A Systematic Review of Cybersickness," in *Proceedings of the 2014 Conference on Interactive Entertainment*, in IE2014. New York, NY, USA: Association for Computing Machinery, Dec. 2014, pp. 1–9. doi: 10.1145/2677758.2677780.

[69] S. Weech, S. Kenny, and M. Barnett-Cowan, "Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review," *Front Psychol*, vol. 10, p. 158, 2019, doi: 10.3389/fpsyg.2019.00158.