

MindFlow: Breathing-Integrated Progressive Muscle Relaxation with a Full-Body Self-Avatar in Virtual Reality

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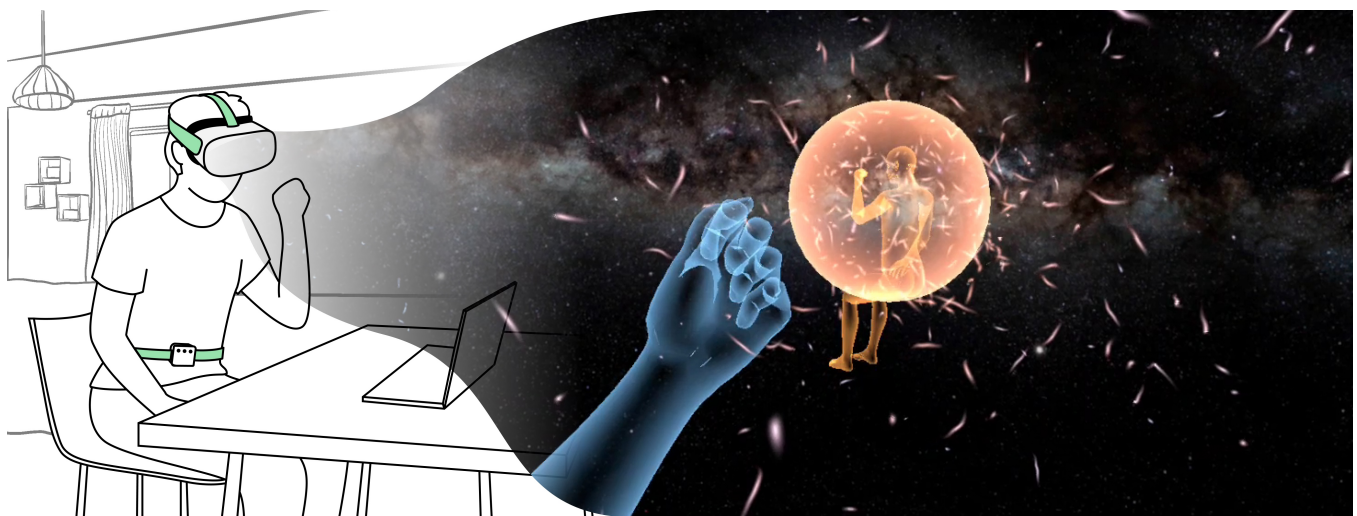


Figure 1: MindFlow offers novice users an immersive and interactive experience for Breathing-Integrated Progressive Muscle Relaxation (PMR) with breathing-based biofeedback and a virtual self-representation.

Abstract

Breathing exercises and Progressive Muscle Relaxation (PMR) have complementary effects, making their integration a common practice among relaxation techniques. While numerous virtual reality (VR) exercises support breathing exercises in self-training, integrating breathing support into PMR in VR presents challenges, including maintaining the user's sense of presence and ensuring the effectiveness of breathing guidance. In this paper, we present *MindFlow*, a system design that combines breathing biofeedback with a full-body self-avatar, using mindfulness-based principles to provide effective, breathing-integrated PMR guidance in VR. The system demonstrates effectiveness in enhancing relaxation and reducing anxiety in novice users, based on empirical results from a

24-participant user study, offering generalizable insights for the design of embodied mindfulness systems and further research on mindfulness support in virtual and mixed reality.

CCS Concepts

• **Human-centered computing** → **User interface toolkits**; **Virtual reality**; **Empirical studies in HCI**; **Interaction design theory, concepts and paradigms**.

Keywords

Progressive Muscle Relaxation, User Experience, Virtual Reality, Embodied Interaction, Mindfulness

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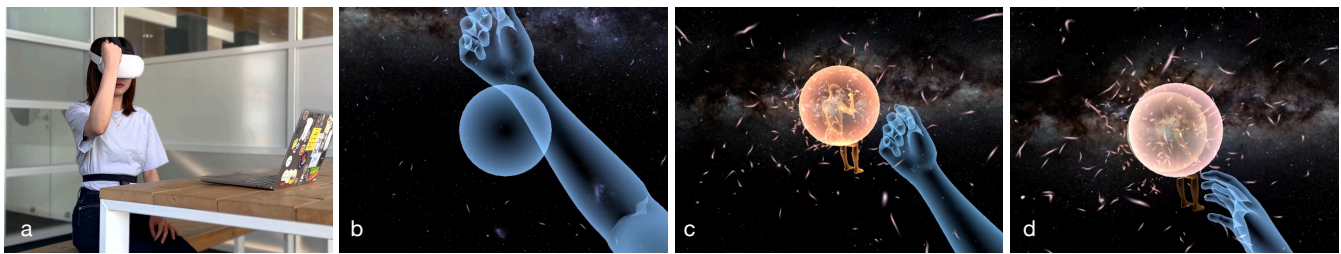


Figure 2: User experience of MindFlow: The user a) wears a head-mounted display and a breath-sensing belt, b) sees the virtual self-representation and breathing, follows the c) pose and breathing instruction to tense their muscle group by making a fist during inhalation, and then d) relaxes their muscle group by releasing the fist during exhalation.

1 Introduction

Breathing exercises [19, 30, 35] and Progressive Muscle Relaxation (PMR) [17, 28] are two widely recognized mind-body practices known for effectively reducing stress and anxiety as well as improving sleep quality. Breathing exercises involve focusing on one's breath, slowly inhaling and exhaling to activate the parasympathetic nervous system and facilitate relaxation. PMR exercises require individuals to systematically tense and release different muscle groups in a specific sequence, focusing on the subsequent relaxation sensation. Matsumoto and Smith [48] demonstrated that PMR enhances physical relaxation and disengagement, while breathing exercises strengthen relaxation intensity and awareness, highlighting their complementary effects.

McCallie, Blum, and Hood [17] note that breathing exercises are often integrated into PMR practices, involving the tensing of muscle groups during inhalation and their relaxation during exhalation. *Breathing-integrated PMR*, also known as PMR with integrative breathing exercises, is a relaxation technique that combines PMR with intentional breathing exercises to deepen physical and mental relaxation. This technique has demonstrated efficacy in alleviating anxiety, decreasing sympathetic arousal for increased comfort, and managing shortness of breath [60]. However, combining breathing and PMR can be challenging, as the two exercises require distinct attention focuses—one on breathing rhythm and the other on muscle sensations. While therapist-led, breathing-integrated progressive muscle relaxation (PMR) sessions have shown to be highly effective, access to these services may not always be available or affordable for everyone. Consequently, individual training with guided support and feedback is increasingly being sought as a more accessible and practical alternative.

Given the increasing affordability, lightweight nature, and comfort of head-mounted display (HMD) technology, incorporating virtual reality (VR) promises an immersive relaxation experience with audio-visual guidance and feedback. However, the crucial challenge in designing breathing-integrated PMR in VR is that users do not see themselves with their eyes open. For body-based exercises such as PMR, the absence of their embodied self in VR may disengage the user [74] and become a limiting factor for grounding their experiences and feelings in the physical body [34, 79].

This study is motivated to improve the breathing-integrated PMR experience in VR with biofeedback and virtual self-representation. We hypothesize that *incorporating a full-body self-avatar can sustain*

the user's sense of presence, and a mindfulness-based design related to respiration and posture feedback can provide effective breathing-integrated PMR guidance in VR that will improve the users' relaxation and keep them engaged in the exercise.

We explored the system design by employing a research-through-design methodology [84], iteratively designing and reflecting on several prototypes of an experiential system design, namely MindFlow (Figures 1 and 2), to unfold the design challenge. MindFlow fills the gap in prior work by offering an embodied mindfulness experience in an immersive environment, integrating breathing-based biofeedback with a *full-body self-avatar* in VR to enhance presence, guidance, and effectiveness in progressive muscle relaxation. It offers an immersive and embodied breathing-integrated PMR experience in VR, utilizing an HMD and a wireless respiratory sensing belt to provide immersive graphics with breathing-based biofeedback and posture feedback through a full-body self-avatar that facilitates the *intimate correspondence* [26] between the VR users' bodily movements and the virtual environment. Targeting novices in PMR who do not already remember PMR procedures by heart, we apply a visual design that adheres to mindfulness-based guidelines [22, 64]. Guidance and feedback on posture and respiration were meticulously designed to support the breathing-integrated PMR exercises.

We iteratively designed and tested the proposed system with users, including a user study involving 24 novice participants. The study results indicate that the proposed seven-minute PMR program effectively guided participants' breathing, enhanced their perceived relaxation, and decreased subjective anxiety following exposure to an acute stressor (i.e., Stroop color-word test [61]). Participants connected to the program through the virtual self-avatar and immersive environment. The interview results show that participants agreed on the clarity of instructions and guidance, leading to attractive and stimulating experiences that facilitated relaxation training. The findings from the design process also reveal tensions and implications for further research and design endeavors.

This work's primary contribution is twofold: 1) the design of the MindFlow system, which enhances the breathing-integrated PMR experience by incorporating breathing-based biofeedback and a virtual self-representation; and 2) the evaluation of its overall effectiveness in inducing relaxation and reducing anxiety, with empirical findings that inform future designs for body-based relaxation systems in virtual or mixed reality.

2 Related Work

This section reviews the embodied interaction design approaches of somaesthetics and mindfulness-based design, breathing exercises in VR, PMR with integrative breathing, and subjective presence in VR. Finally, we summarize the research gap and formulate the research hypothesis.

2.1 Somaesthetics and Mindfulness-based Design

The third wave in HCI [9] brought the embodied approach to interaction [21], which has had a prominent influence on how and why bodies matter [37]. Somaesthetics theory [68] explores body consciousness and somatic practices and demonstrates how they can lead to fulfilling mindfulness experiences. Accordingly, Hook et al. [26] introduced three guidelines for Somaesthetic Appreciation Design: *subtleness*, which encourages and spurs bodily inquiry in the choice of interaction modalities; *making space*, which involves shutting out the outside world; and creating an *intimate correspondence* between movement and interaction.

Mindfulness-based design also encourages a shift of attention inward towards bodily sensations to support well-being and self-regulation processes [16], fostering a non-judgmental state to accept and be present in the moment-to-moment unfolding of experiences [31]. In mindfulness research, the terms *embodied mindfulness* [34] and *embodied cognition* [79] both denote the grounding of all experiences and feelings in the physical body. Mindfulness-based design has evolved around focused-attention meditation (FAM) [39, 44, 47], a practice of sustaining focused attention on a single object of focus. FAM involving breathing is a widely accepted practice to cultivate a sense of presence and is considered the most accessible practice for novice meditators [47].

To support mindfulness-based design and HCI research in mixed reality, Roo et al. [64] developed seven design guidelines in collaboration with experts, focusing on Distraction vs. Guidance, Keeping it Minimalist, Non-judgment and Non-striving, Promoting Acceptance, Promoting Autonomy, Using Tangible Interaction, and Choosing the Right Reality. These guidelines aim to guide implementation and support future research exploration. Döllinger et al. [22] further synthesized design guidelines for digital mindfulness based on a review of existing frameworks and guidelines, including Niksirat et al.'s [52, 66] attention-regulation framework, Zhu et al.'s [82] framework on four levels of digital mindfulness, and Roo et al.'s seven guidelines for designing mindfulness practices and experiences in mixed reality.

2.2 Breathing Exercises in VR

Engaging in breathing exercises influences cognition, memory, and emotional processing [30, 55, 81], offering benefits such as decreased anxiety and stress [30, 35]. Attention to one's breathing can reduce mind-wandering and support mindfulness [41, 56, 58], with demonstrated impacts on mental health and well-being [63]. VR technology leverages its immersive qualities—such as a consistently low-latency sensorimotor loop between sensory data and proprioception, plausible natural scene imagery, and appropriate correlations between participants' actions and environmental responses over time [70] to engage users in a flow state within a VR

system. Moreover, since VR is able to help its users minimize external distractions and develop nonjudgmental self-awareness [4], it emerges as a new platform for biofeedback therapy [45]. As immersion can lead to “*a state of deep mental involvement*” [2], VR has the potential to facilitate mind-body practices [5], which can reduce feelings of tension, alleviate the impact of anxiety, and promote mindfulness [75].

Commercial VR breath training apps, such as TRIPP¹ and the Mindfulness app of Apple Vision Pro², provide an immersive virtual environment that solely indicates breathing guidance. Apps such as Guided Tai Chi³ further incorporate posture guidance and sensing. However, they do not provide reliable respiration biofeedback for people to reflect on their breathing performance.

Recent HCI research has explored respiration sensing as an interaction modality and for providing biofeedback in VR games [54, 73, 78] leading to the development of VR-based breathing exercises that emphasize breath awareness and interactive breathing techniques [50, 57–59]. For instance, DEEP [77] explores breathing to reduce children's anxiety. Life Tree [54] guides users to synchronize their breathing with audiovisual guidance to practice pursed-lip breathing [14] with performance feedback. Attending to Breath [59] links breathing to audiovisual feedback to explore the emotional impacts of breathing biofeedback in VR. InnerGarden [64] is a multisensory mixed-reality environment where users' breathing and heart rate dynamically shape the virtual world. Rockstroh et al. [62] gamified respiratory biofeedback to teach diaphragmatic breathing in an immersive virtual environment [24]. BreathCoach [76] is a smartwatch-based VR experience providing at-home coaching for biofeedback-based paced breathing training. Stairway to Heaven [50] emphasizes the therapeutic potential of diaphragmatic breathing by using a respiratory sensor belt around the abdomen.

These applications capture breathing in VR primarily through stretch sensors (e.g., [50, 64]) to free users' hands for interaction while providing reliable measurement. Breathing can also be measured using airflow sensors (e.g., [54]) or the inertial sensors in VR controllers (e.g., [62]). Nonetheless, all these applications provide a first-person perspective in an immersive virtual environment with biofeedback. Still, without providing a bodily representation (e.g., a full-body avatar) of their users, their sense of presence is limited when they need to pay attention to their bodies. Döllinger et al.'s systematic review [22] also highlighted that virtual self-avatars have not yet been sufficiently implemented in relaxation programs.

2.3 PMR with Integrative Breathing

Progressive Muscle Relaxation (PMR) training was developed by Edmond Jacobson [28] and later adapted and shortened by Joseph Wolpe for *systematic desensitization*, a behavioral therapy addressing fear and anxiety [80]. The training incorporates tension-release cycles, exemplified by making a tight fist followed by release. McCallie, Blum, and Hood [17] note that breathing exercises are often integrated into PMR practices, emphasizing controlled breathing, involving the tensing of muscle groups during inhalation and their relaxation during exhalation. This practice has shown efficacy in

¹<https://www.tripp.com/>

²<https://www.apple.com/apple-vision-pro/>

³<https://www.meta.com/en-gb/experiences/guided-tai-chi/1756328964489238/>

alleviating anxiety, decreasing sympathetic arousal to increase comfort, and managing shortness of breath [60]. Research on PMR explores its impact on various conditions, including cardiac issues, insomnia, chronic pain, and anxiety [17]. Bernstein et al. [7] identify individuals with disruptive tension responses as suitable candidates for relaxation training. Imam et al. [27] found that PMR significantly reduces anxiety and improves sleep in COVID-19 patients. Clinical studies such as those by Gopichandran et al. [23] also demonstrate how deep breathing, along with PMR, can help chronic tension-type headache patients relieve pain severity and frequency, resulting in better sleep quality over a 12-week follow-up.

Novice users need to be guided to follow the PMR procedures, and individuals typically follow them using audio or video recordings. They sit comfortably, maintain calmness, avoid distractions, and take three to five abdominal breaths before starting the relaxation process. During the session, they alternately tense and sequentially relax sixteen muscle groups throughout the body. Sessions conclude with a brief reflection, recalling the sensations associated with releasing muscle tension in previous exercises [6].

Little research has been conducted on applying VR for PMR. For example, Jeong et al. [29] conducted a 3-week feasibility study on VR-based self-training using a non-interactive PMR instruction video overlaid on 360° videos of real-world recordings. This approach helped educate healthy individuals to train in PMR practices independently and showed potential effectiveness in a simulated outdoor environment. Nonetheless, the user experience was limited by the lack of feedback on user performance.

2.4 Subjective Presence in VR

The most important factor behind presence in VR is perception through natural sensorimotor contingencies. The more the body is directly involved in the interaction process, the more natural the virtual experience [71]. For exercises that involve the human body in VR, visualizing self-representation is crucial for users to retain their sense of presence — an illusion of *being in the virtual world* [25, 69]. To provide VR users with a sense of virtual embodiment [36, 65], which consists of their senses of self-location (being located at the position of one's body in the virtual environment), agency (controlling one's own body movements), and body ownership (conscious experience of self-identification), a common practice involves a dynamic representation of oneself from a first-person perspective, typically seen as a computer-generated hand. As Bricken [15] suggests, the virtual hand (ideally, the virtual body) serves as a functional point of reference for our location in cyberspace, and “*it is compelling to see your virtual fingers move as you wiggle your hand. Watching your dynamic self-representation within the virtual world is convincing evidence that you're there.*”

The study of Steed et al. [74] indicates the benefit and necessity of having a virtual self-avatar to perform cognitive tasks. Participants memorized pairs of letters while performing spatial rotation exercises with or without avatars and the ability to move their hands (in place or not). The results showed that those who had an avatar and moved freely recalled more letter pairs than others, suggesting a positive effect of virtual self-representation on cognitive performance. Without a visible self-representation, their

users either refrained from or stopped hand movements shortly after initiation. The results are evidence of the importance of an appropriate self-avatar representation in immersive virtual reality and motivate our research in the targeted application.

2.5 Summary and Research Hypothesis

PMR with Integrative Breathing introduces emerging design challenges in VR. While users perform these exercises with their eyes open to follow breathing guidance, they cannot see their embodied selves in the virtual environment. This absence challenges their sense of presence and engagement with their bodies. From the perspective of somaesthetic design [26], VR without self-avatar disrupts the user's visual perception and the intimate connection between their bodily movements and the virtual space. Self-avatar is thus crucial in this design context.

Next to self-representation, displaying respiration and posture guidance and feedback to users is crucial. Miner et al. [50] reported that users of the *Stairway to Heaven* system did not always adhere to the respiratory biofeedback displayed at the center of the HMD view, even though it was essential for progression. Instead, users gravitated toward other aspects, such as relaxation and the mindfulness audio guide, finding it difficult to focus on their breathing. This challenges the initial conception of biofeedback's role. Adapting existing research on mindfulness-based design in mixed and virtual reality may provide a fresh perspective to address the limitations of displaying biofeedback on the screen. Therefore, we formulate our research hypothesis as follows:

Hypothesis: Incorporating a self-avatar can sustain the user's sense of presence, and a mindfulness-based design related to respiration and posture feedback can provide effective, breathing-integrated PMR guidance in VR.

3 Designing MindFlow

Considering the adaptation issues of *novice* users, we aim to enhance the conventional breathing-integrated PMR experience by mandating users to wear minimal devices (e.g., HMD and a respiration sensor) before commencing their PMR session. They will then engage in breathing-integrated PMR exercises with immersive interactive graphics that assist novice users in visually comprehending audio instructions, providing higher-quality and enriching stimuli in their experiences.

Designing such a system posed challenges, particularly concerning implementing traditional breathing-integrated PMR exercises and the experiences we aim to create. This section addresses the design requirements, our initial design iteration with findings and feedback gathered from a user group, and the second iteration with a heuristic evaluation.

3.1 Design Requirements

We first reviewed the design guidelines on digital mindfulness supports proposed by Döllinger et al. [22], which was synthesized based on a review existing frameworks and guidelines, including Niksirat et al.'s [52, 66] attention-regulation framework, Zhu et al.'s [82] framework on four levels of digital mindfulness, and Roo et al.'s seven guidelines on designing mixed-reality mindfulness practices and experiences in mixed reality [64]. Döllinger et al.'s

guideline provides 14 checkpoints for designing mixed-reality mindfulness tasks related to the general design, guidance, feedback, and interaction, which is comprehensive and relevant to our research. However, we found the complete list of design guidelines somewhat burdened with our initial design exploration, as too few initial ideas could pass the full test. Therefore, we decided to use Dollinger's complete guidelines as an analytic tool to evaluate our design outcomes. Instead, we select Roo et al.'s seven guidelines [64] as an entry point for our design process. The guidelines are 1) distraction vs. guidance, 2) keeping it minimalist, 3) non-judgment and non-striving, 4) promoting acceptance, 5) promoting autonomy, 6) using tangible interaction, and choosing the right reality.

We also noticed that Roo et al.'s guidelines are relevant yet may not fully apply to our application needs because breathing-integrated PMR exercises consist of a wider range of bodily inputs involving breathing, posture changes, and muscle contractions. Therefore, we also incorporate the Somaesthetics Appreciation Design guidelines [26] to design for *subtleness*, *making space*, and *intimate correspondence*. Additionally, we target optimizing novice users' experiences to address the research gap discussed in related work. Therefore, we modified these seven design guidelines into five design requirements (R[1-5]) for the target experience as follows.

R1. Clarity in Instruction, Minimal Distraction. We aim to *augment* audio guidance with immersive graphics to reduce cognitive loads for novice users. Given their unfamiliarity with the PMR procedure, we prioritize clarity in instruction, offering direct guidance on body movement synchronized with breathing, muscle tension, and release. The goal is to provide subtle yet effective guidance and feedback that minimally distract users' focus of attention on their pace of breathing and the muscle group they are using. This requirement is adapted from Roo et al.'s guideline #1 *Distraction vs Guidance* [64] and Hook et al.'s guideline *subtleness* [26].

R2. Balancing Minimalism and (Visual) Immersion. Roo et al. [64] advocate using a minimalist visual style that reduces visual distractions, enhancing user focus on tasks. Employing audiovisual stimuli that do not necessitate prior knowledge of the presented narrative is crucial to prevent disinterest and confusion [2]. Nonetheless, within an intimate, personal, and spacious space made in VR that shuts out the outside world, avoiding oversimplification, such as employing a blank background, is important to ensure the user maintains a sense of presence in the virtual environment. This requirement is adapted from Roo et al.'s guideline #2 *Keeping it Minimalist* [64] and Hook et al.'s guideline *making space* [26].

R3. Promoting Acceptance without Judgment or Striving. The program promotes an inviting, non-evaluative approach, avoiding explicit session assessments and refraining from setting specific goals to align with a non-striving attitude. Instead, it should invite users to reflect and accept the current moment (presence-in and presence-with) [83] and their current state. This requirement is adapted from Roo et al.'s guideline #3 *Non-judgment and Non-striving* and #4 *Promoting Acceptance* [64].

R4. Avoiding Tangible Interaction. Handheld controllers and external props can be cumbersome for novice users less familiar with HMD technology. Getting familiar with using these external

objects and knowing their tracking limits may draw too much attention from the users. Therefore, we have chosen not to incorporate tangible interaction into our program. Instead, the users rely on their own body for interaction, utilizing muscle contraction and self-haptics, such as making a fist, to increase the intimate correspondence and draw attention inward to their body to enhance their sense of virtual embodiment [12]. This requirement is revised from Roo et al.'s guideline #6 *Using Tangible Interaction* [64] and Hook et al.'s guideline *intimate correspondence* [26].

R5. Choosing the Right Reality. Modern HMDs provide complete immersion in virtual reality (VR) and mixed reality (XR) with a see-through mode, accommodating various designs along the reality-virtuality continuum [49]. In VR, users are immersed in a digitized environment, free from real-world distractions, but their sense of *being there* is limited by the absence of self-visualization. In XR, users perceive themselves in their familiar surroundings alongside digital enhancements, although they may encounter visible distractions if not managed. This requirement is adapted from Roo et al.'s guideline #7 *Choosing the Right Reality* [64].

As we aimed at novice users, our initial design requirement left out Roo et al.'s guideline #5 *Promoting Autonomy* [64], which aims to allow more experienced users to control the boundaries of the experience along with when and how the feedback occurs. We will revisit it in a later discussion.

3.2 First Iteration

We developed the initial version of MindFlow and implemented an experimental proof-of-concept system, adhering to the specified design requirements.

3.2.1 Design.

Focusing on Both Hands and Arms. Commodity HMDs, like Meta Quest headsets, offer robust and responsive tracking for both hands, allowing users full dexterity. This capability supports users' senses of self-location, agency, and body ownership [36]. A comprehensive PMR exercise necessitates physical engagement beyond hand gestures, as detailed in Section 2.3. We tried incorporating external cameras, like a time-of-flight depth camera (e.g., KinectV2), or a webcam enhanced with a pose recognition machine learning algorithm (e.g., OpenPose [18]) and meticulously calibrated them to maximize support for track points. However, the full-body tracking performance included additional jitters and latency and did not encompass all body parts and joints. Therefore, this research solely targets the upper body parts of the PMR exercise, specifically focusing on muscle groups associated with the user's hands and arms, which comprise the initial four out of the 16 muscle groups exercised of a complete PMR exercise [17]. This serves as a condensed 4-minute version of PMR relaxation as a proof of concept.

Virtual Environment with Self-Representation. Digital mindfulness support should encourage users to feel present with objects or within a natural or digital environment that inherently promotes mindfulness [83]. Therefore, we have created a spacious, private galaxy with the Milky Way and ambient sound as the background (R2). To promote bodily awareness, which is crucial in mindfulness training [53], we provide a real-time representation

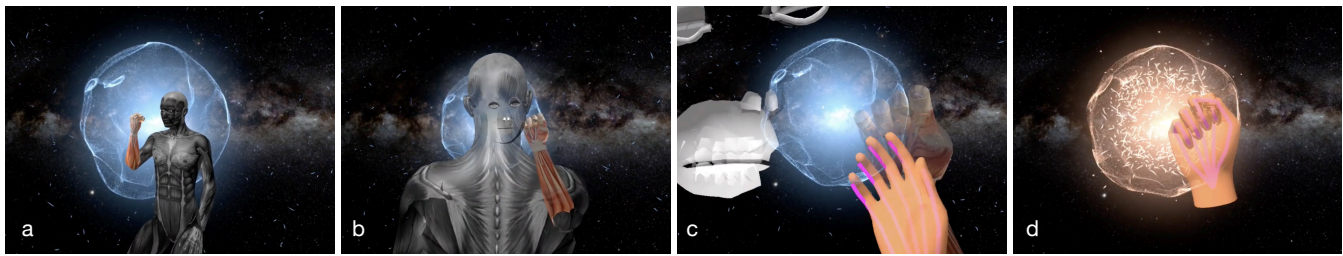


Figure 3: First iteration design on the transition from the instruction to the practice session: a) The instructional body model demonstrates body movements through animation and highlights the muscle group, then b) rotates and shifts to return to the user's orientation and position, and finally c) dissolves while the virtual self-representation (hand model) blends in. d) The user employs the pose and breathing instructions and follows the breathing guidance throughout the muscle tensing and releasing. At the beginning of the next session, the view transition reverses from d) to a).

of the user's hands from their first-person perspective as their self-representation by leveraging responsive hand tracking from the HMD. Virtual hand posture and location are updated in real-time while users listen to calm background music and vocal instructions for the PMR procedures.

In the initial session, which targets the dominant hand and forearm muscle group, the right-handed user forms a fist with their right hand (**R4**). They engage and release their forearm muscles in accordance with voice commands. Upon hearing the instruction to “*breathe in*,” users contract their muscles and inhale simultaneously. Conversely, upon hearing the instruction to “*breathe out*,” they release their fist and muscles, exhaling simultaneously. This cycle of tension and release persists until the session comes to an end.

Visual Pose Instruction. Given that virtual hands alone are insufficient to represent the entire body fully and auditory guided meditation alone isn't adequate for successful digital mindfulness support [67], we incorporate a full-body avatar to visually guide users in their body poses (**R1**). Building on findings from a prior study [20] suggesting that displaying photorealistic avatars and mirrors can lead individuals to overly focus on their appearance rather than their internal body signals, thus negatively impacting users' body awareness, we opt against presenting personalized avatars resembling the user and refrain from employing virtual mirrors. Therefore, we attempted to utilize a monochrome human model to emphasize the muscle group engaged in the session and crafted a smooth transition between the instructional and practical phases. Figure 3 illustrates the transition from pose instruction to the practice session: a self-avatar shifts and rotates from the user's position to the forefront, demonstrating the movement in synchrony with the voice-guided pace through 3D animations depicting the required poses. After completing the instruction, the self-avatar returns to the user's original orientation and position. Subsequently, the virtual self-representation (hand model) smoothly integrates to indicate the user's control. The view transition cycles back and repeats at the start of the next session. Throughout the exercise, the program refrains from offering explicit suggestions or evaluations of the user's performance; instead, it provides feedback solely on their bodily posture via their virtual hands (**R3**).

Visual Breathing Guidance. Accompanying the PMR guidance, the associative breathing guidance should be intuitive yet not distract the user's focus on the muscle tension-and-release cycles [17]. Audio guidance has been utilized in guiding PMR exercises. Therefore, we designed *subtle* yet rich visual breathing guidance in the background (**R2**) using a swarm of dynamic particles in a spherical form, simulating airflow as depicted in Figure 3. The user inhales when the sphere is expanding and exhales when the ball is shrinking, and the particles gather to the center and disperse from the center accordingly (**R1**). This visually captivating guidance is perceivable in the users' peripheral vision and synchronized with the voice guidance.

Integration with the HMD's Pass-Through Mode. To explore this design in mixed reality, we also implement a VR-pass-through version as an alternative using the HMD's pass-through view. This feature allows users to see their own bodies alongside the hand model during the exercise (**R5**). While the pose instruction remains in virtual reality, once it concludes and the full-body avatar returns to the user's position, the VR mode seamlessly blends into the pass-through mode. This transition enables users to observe their entire body while performing muscle relaxation. The visual breathing guidance ball and audio instructions persist throughout the pass-through mode. After completing their practice, the pass-through mode smoothly transitions back into VR mode to display immersive instructions in the virtual galaxy.

Program Overview. Building upon the common practice introduced in Session 2.3, we have developed a 7-minute program comprised of three phases:

Phase 1 (1.5 minutes): Breathing Relaxation. During this phase, the user familiarizes themselves with the virtual environment and interaction mechanism. They engage in paced breathing at six breaths per minute [72] while observing a galaxy with moving stars to induce a sense of calmness.

Phase 2 (4 minutes): Breathing-Integrated Muscle Relaxation. The user then receives instructions and follows guidance to relax specific muscles twice in the following sequence: 1) Dominant hand and forearm: Forming a fist with their dominant hand; 2) Dominant biceps: Elevating their dominant forearm up to their shoulder, creating a muscle contraction; 3) Nondominant hand and forearm:

Making a fist with their non-dominant hand; and 4) Nondominant biceps: Raising their non-dominant forearm to their shoulder, creating a muscle contraction. Each position requires approximately 1 minute.

Phase 3 (1.5 minutes): Breathing Relaxation and Reflection. By the end of session, we *make space* [26] for the user to reflect on their practice. The user is guided to reflect on their muscle sensations, regulate their breathing using the breathing ball, and focus on different muscles as instructed. As the exercise ends, prolonged chime sounds signal the conclusion and remind users to remove the HMD and return to physical reality.

3.2.2 Implementation. Our implementation uses a Meta Quest 2 head-mounted display with built-in hand-tracking capability and a monochrome pass-through mode. The VR application is developed using Unity, with 3D models obtained from Free3D⁴ and edited in Maya. Voice guidance is generated using the Murf AI voice generator⁵, based on instructional scripts adapted from McCallie et al. [17] and Connelly's online video⁶. Ambient background music is a 528 Hz sample from Zen Life Relax⁷, chosen for its proven stress-reducing effect [3].

3.3 Preliminary User Study

3.3.1 Method. We elicit preliminary user feedback on our prototype and its design from four participants recruited: Participant P1 (69 years old, male) is an expert in PMR exercises with over thirty years of experience. P2 (23 years old, female) is knowledgeable about mindfulness relaxation practices and has one year of experience in PMR exercises. Participant P3 (25 years old, female) was unfamiliar with PMR but had over three months of experience in other mind-body practices. Participant P4 (25 years old, male) had no experience in stress relaxation exercises but over 1.5 years of VR design and development expertise. We let these users use the software implemented on a Meta Quest 2 head-mounted display. The session involved obtaining consent from all participants and introducing them to PMR through Connelly's video using the head-mounted display. Then, participants experienced the Pure-VR and VR-Passthrough versions for seven minutes each, with the order counterbalanced. Semi-structured interviews were conducted post-experiment to gather users' opinions on the prototypes. Participants were individually asked to elaborate on their experiences. The example interview questions are "What do you like about the design" and "What do you dislike about the design."

Thematic analysis [13] in this study employed an inductive approach, allowing themes to emerge directly from the data without preconceived theories. This method enabled the exploration of user experiences and the impact of the MindFlow system on relaxation and engagement levels. The flexibility of this approach helped identify unexpected patterns and themes beyond existing theoretical frameworks. Two authors collaborated throughout the analysis, ensuring coherence and consensus. Both researchers familiarized themselves with the data by reading interview transcripts, independently generating initial codes, and later refining the themes

together. This process involved categorizing the codes into overarching themes and collecting relevant data extracts for each. Discrepancies in the coding were resolved through open discussion and re-evaluation. This approach ensured a comprehensive representation of the experiences of the participants while maintaining methodological integrity.

Ethical approval from an institutional review board and consent was obtained from all participants before the user evaluation.

3.3.2 Results. All four participants completed the experiences and provided feedback during the interview. The key findings are highlighted as follows.

Pure-VR vs. VR-Passthrough. All participants noted that the Pure-VR version offered a more immersive experience compared to the VR-Passthrough version and the 2D video. Three out of four participants mentioned that the 3D virtual environment helped them quickly achieve a state of relaxation. Participants unanimously appreciated the virtual environment and background music, with Participant P2 stating, "*The coherent visual and audio of the scene made me feel relaxed and immersed.*" However, three out of four participants expressed dissatisfaction with the monochrome and blurry appearance of the real environment, noting that it did not align well with the overlaid visuals, thus disrupting the immersion and causing distractions. Nonetheless, one participant out of four recognized the value of the VR-Passthrough mode because the depiction of the real world offered a sense of safety.

Visual Guidance. Regarding the visual guidance, all participants expressed that the pose instruction was clear and easy to understand in conjunction with the voice guidance. Participant P3 noted, "*When the human model is overlapping with me, I get a strong sense that I am her.*" Three (out of 4) participants indicated that the virtual hands helped them connect with and feel their real hand in the virtual world. All four participants also acknowledged the effectiveness of visual breathing guidance, as participant P2 expressed, "*The breathing ball is easy to understand, and it didn't take much of my attention.*" However, 2 (out of 4) participants wanted to monitor their own breathing, as participant P4 mentioned, "*I feel uncomfortable and distracted when there is a big difference between my breathing and the breathing ball.*"

On the flip side, participants also highlighted several factors that diminished their satisfaction with the usage. Two (out of 4) participants reported feeling less connected to their muscles during the upper arm exercise due to the absence of a corresponding upper arm representation, leading them to imagine where their upper arms should be. Three (out of 4) participants mentioned that the appearance of the human model deviated from the environment and was perceived as overly detailed, even reaching the point of being perceived as scary because it was "*too detailed*" (P2). Participant P3 also mentioned, "*I was distracted because I wanted to use the exact muscle that is highlighted in the model, and it took all my attention, and I forgot to adjust my breathing.*" Moreover, three (out of 4) participants noted that the avatar's movements toward and away from their body contributed to information overload. Participant P1 expressed concern about the avatar's movement, as it reminded him of out-of-body experiences [8].

⁴<https://free3d.com/>

⁵<https://murf.ai/>

⁶<https://youtu.be/ihO02wUzgkc>

⁷<https://youtu.be/4sCKNLc1suQ>

Phase Setting. All participants gave positive feedback regarding the current phase setting in the program, with participant P3 specifically mentioning, “These phases helped me switch between different statuses fluently.”

Summary. Preliminary user feedback revealed that the prototype system facilitated their experiences in the breathing-integrated PMR exercise. Participants could follow the instructions and immerse themselves in the virtual environment, guided by audio-visual cues on adjusting breathing and feeling muscles. Some expressed a desire for feedback to enhance their breathing techniques. Virtual hands and a body avatar enhanced users’ connection to the virtual world and increased their bodily awareness. However, participants suggested further simplifying the body avatar’s appearance to minimize distractions. The Pure-VR prototype received better feedback because VR passthrough experiences were limited by distractions from the surrounding environment and the blurry monochrome display of the experimental apparatus, overshadowing the benefits of observing their body during the PMR exercise.

3.4 Second Iteration

Building upon the findings of the first iteration, we have developed *MindFlowV2* to explore the design space further. *MindFlowV2* (Figure 4) has been designed and implemented by enhancing three key aspects of the *Pure-VR* prototype proposed in the initial iteration. It utilizes a full-body self-representation with a simplified appearance, incorporates a distinct full-body avatar and redesigned visuals for pose and procedural instruction, and integrates visual breathing guidance with real-time respiration biofeedback.

3.4.1 Redesigned Features.

Full-Body Self-Avatar. To enhance users’ visual perception of the location of their body parts, the second iteration utilizes a full-body avatar connected to both hands via inverse kinematics (R1). The full-body avatar is a gender-neutral humanoid model rendered in cyan color with a semi-transparent fill, excluding unnecessary details such as muscles, to let users focus less on the avatar’s appearance. During the four sessions of upper-body breathing-integrated PMR, the hands and arms of the self-representation are continuously updated in real-time according to the user’s posture, thereby ensuring a heightened sense of embodiment.

Separate Instruction Avatar. During pose instructions, an orange instruction avatar, identical in shape to the self-avatar, gradually appears in front of the user and displays the posture instructions synchronized with the voice-guided pace through 3D animations. To minimize distractions during the pose instruction phase, the duplicated model remains static instead of moving towards or away from the user (R1). Once the instruction is complete, the duplicated self-avatar gradually fades away and disappears. To prevent visuals from appearing too simplistic, dynamic particles improve the appearance and disappearance of the instruction avatar, creating more captivating visuals and reducing predictability (R2). The disappearance of the instruction avatar signifies the beginning of the user’s practice.

Visual Breathing Guidance and Feedback. Despite the positive reception of previous practical-based breathing guidance, combining

both breathing guidance and feedback became overly complex. To offer clear instructions and feedback, we now present the breathing guidance and feedback in two semi-transparent bubbles (R1). The guidance bubble shares the same orange color as the instruction avatar, while the feedback bubble matches the cyan color of the user’s self-representation. As the orange and cyan bubbles symbolize the instructor’s and user’s lungs, respectively, the orange bubble remains positioned at the instructor’s location, while the cyan bubble follows the user’s visual center. Metaphorically, the bubbles contract during exhalation and expand during inhalation, and the users synchronize their breathing according to the guidance. Additionally, we maintain *subtle* [26] oscillations of stars in the background synchronous with the breathing guidance (R2) to allow users to follow the guidance without focusing on the instructor. The user follows these rhythmic breathing guidance and synchronizes their breathing, creating an *intimate correspondence* [26] in between.

As in the first iteration, the program does not aim to offer quantified metrics of users’ performance. Instead, it provides feedback on their bodily posture via their virtual hands and their breathing via the cyan bubble (R3). We also refrained from filtering or smoothing the respiration sensor data to enhance acceptance, reflecting the actual physiological state, similar to InnerGarden [64] (R3).

3.4.2 Implementation. *MindFlowV2* is also implemented using a Meta Quest 2 head-mounted display. Respiration sensing is accomplished using an Elastech wireless respiration sensing belt⁸, which features a 0.92 mm-thick capacitive stretch sensor with a linear signal response up to a 30% stretch range, a lifecycle of 1.5 million stretches at 3%, and 1.5–2 hours of usage on a full charge. The sensor gathers stretch sensor readings at 20Hz with a 50ms latency and transmits them to a laptop via Bluetooth for a respiration signal processing software program on the laptop. The Java-based software collected a window of 15 seconds at a sample rate of 20 Hz, used the local extrema to normalize breathing amplitude to provide biofeedback, and then sent the normalized signal to the HMD via Wi-Fi.

3.4.3 Heuristics Evaluation. Inspired by Nielsen’s heuristic evaluation methodology [51], we use the mixed-reality mindfulness design guidelines proposed by Döllinger et al. [22] as heuristics to evaluate the design of *MindflowV2*. As the software consists only of components of *virtual environment* and *virtual self-representation*, we evaluate these two components in its four categories: *design*, *guidance*, *feedback*, and *interaction*. Two authors were involved in the discussion, and their agreement is presented as follows.

- *General design:* The virtual environment of *MindflowV2* uses immersive graphics and multimodal guidance with minimal visual design to direct the users’ attention to themselves. The virtual self-representation is also minimally designed as a gender-neutral presentation to let the users focus less on the avatar’s appearance.
- *Guidance:* The virtual environment of *MindflowV2* uses subtle and peripheral breathing guidance (i.e., moving stars) to complement the breathing and posture guidance when the users look at the avatar. The posture instruction also uses a

⁸<http://www.elas-tech.com>

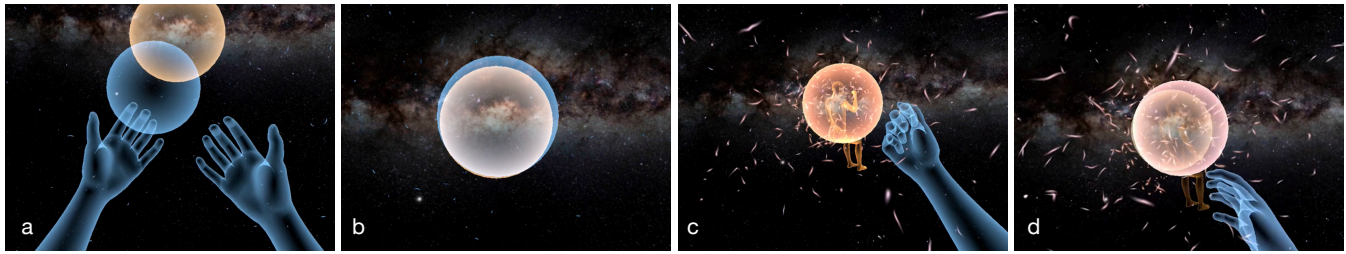


Figure 4: Second iteration design on the transition from practice to instruction in virtual reality, using the MindFlowV2 prototype: a) The self-representation employs a full-body avatar connected to both hands through inverse kinematics; the cyan breathing bubble is overlain at the center of the user’s view. b) Users control their breathing according to the orange instruction bubble. c) The instruction model blends in and displays the pose with visual cues on the timing of muscle contraction, and then d) dissolves again to signify the user to take over. The transition from instruction to practice is from d) to c).

similar avatar representation as the user’s self-avatar as posture guidance with the same body formation that minimizes the user’s cognitive load.

- **Feedback:** Regarding posture feedback, the posture and movement of virtual self-representation directly map to the user’s posture and movement, facilitating the user’s body awareness. The breathing feedback uses a minimal blue circle looked similar to the breathing guidance. We do not add extra environmental feedback to augment the user’s posture so users can better focus on those presented to them already.
- **Interaction:** The user performs body-based input methods, including breathing, body movement, and muscle contraction, while performing the slow, repetitive exercise during breathing-integrated PMR. The user is always free to explore the environment by turning their head, looking around, or closing their eyes to enjoy inner peace. The user does not use external physical input devices during the breathing-integrated PMR exercise.

Walking through these heuristics, we have demonstrated that the current design generally meets the mixed-reality mindfulness design guidelines proposed by Döllinger et al. [22].

4 Evaluation with Users

MindFlowV2 offers immersive and embodied breathing-integrated PMR and breathing exercises in a seven-minute format. To explore its efficacy and user experiences, we conducted a formal user study to understand whether this seven-minute exercise effectively enhances relaxation and alleviates anxiety for our target users: novice users of breathing-integrated PMR exercises after encountering an acute stressor.

4.1 Method

4.1.1 Apparatus. The user studies were conducted in a quiet, private meeting room at the University. A Meta Quest 2 head-mounted display was employed to deliver the VR experiences. We utilized an Elastech respiration sensing belt to collect the respiration data, transmitted the data to a laptop via Bluetooth, and subsequently relayed it to the head-mounted display via Wi-Fi.

4.1.2 Pilot Study. Before the formal study, we recruited two participants (one male and one female) to evaluate the process and usability of the apparatus. Observations and participant feedback indicated that instructions concerning minimizing movement and maintaining normal breathing during the baseline session should be included to ensure accurate measurements.

4.1.3 Participants. Twenty-four participants (10 males and 14 females) are recruited in the formal study. All participants had either less than one month or no experience in PMR and were either university researchers or students. Ethical approval from an institutional review board and consent were obtained from all participants before the user evaluation.

4.1.4 Procedure. The experiment spanned 30 minutes and comprised three sessions. Each session began with an introduction and explanation. The participant was then instructed to wear a respiration strap sensor and proceeded with a calibration session, where we created an avatar according to the body height and asked them to raise their arms up to initialize the avatar’s inverse-kinetics algorithm before the session started. During session 1, the participant sat quietly for 8 minutes to establish a baseline. Session 2 involved performing the Stroop color-word test [61] for 5 minutes to induce stress responses. Following this, in session 3, the participant underwent a brief trial and then a 7-minute breathing-integrated PMR training session with the MindFlowV2 system.

4.1.5 Measurements. For each session, we collected participants’ physiological data and self-reports on anxiety and relaxation levels. Following their experience, they were instructed to complete the User Experience Questionnaire (UEQ) [38]. Upon completion of the experiment, qualitative data about their user experience was gathered through interviews.

Physiological Data. The physiological measure, the respiration rate, was recorded in all three sessions, with the respiration strap sensor on the abdomen. For offline signal processing, we inspect the data and calculate the respiration cycle from time-series data by identifying the peaks (inhalations) or troughs (exhalations) in the data and then determining the respiration rate based on the session length.

	Respiration Rate (cycle/min)			RSS (1=least 9=most relaxed)			STAIS-5 (5=low, 20=high stress)		
	Baseline	Pre-PMR	PMR	Baseline	Pre-PMR	Post-PMR	Baseline	Pre-PMR	Post-PMR
Median	11.67	15.15	5.79	7.00	5.00	8.00	6.50	7.00	5.00
Std Dev	3.15	3.67	0.38	1.53	1.79	1.61	2.32	2.54	1.06
Min	7.63	8.50	5.33	3.00	2.00	2.00	5.00	5.00	5.00
25th Pct	9.45	13.38	5.70	6.00	3.75	7.00	6.00	7.00	5.00
75th Pct	14.35	18.00	6.00	7.00	6.00	9.00	8.00	10.00	6.25
Max	19.17	22.00	7.00	9.00	8.00	9.00	16.00	15.00	9.00

Table 1: Descriptive statistics for physiological measures and self-reports regarding relaxation and anxiety.

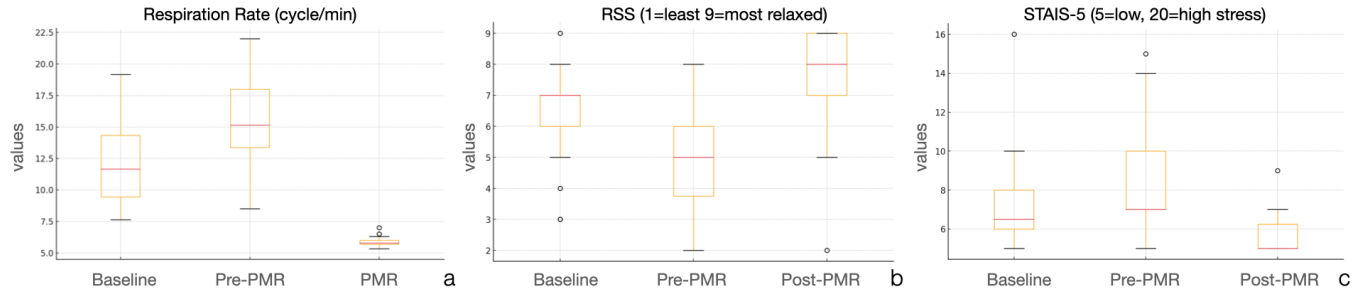


Figure 5: Box plots of results on physiological measures and self-reports regarding relaxation and anxiety.

Self-Report on Anxiety and Relaxation. After each session, we evaluated the participant's levels of anxiety and relaxation using the Relaxation Rating Scale (RRS) [40] and the short version of the State-Trait Anxiety Inventory (STAIS-5) [85]. The RRS is a self-reported measure where participants rate their level of relaxation on a Likert-type scale ranging from 1 (not relaxed at all) to 9 (totally relaxed). Higher RRS scores indicate higher levels of relaxation. STAIS-5 is a 5-item self-report survey that measures current feelings using a 4-point Likert-type scale (1 to 4 points) for each item. In the range of 5 to 20, higher scores on the STAIS-5 indicate higher levels of anxiety and stress.

User Experience. The user experience was evaluated through quantitative data from the UEQ and qualitative data from interviews. The UEQ comprises a 26-item survey that assesses participants' product or experience across six scales: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. Higher scores on each scale denote a better user experience in that specific aspect, ranging from -3 (negative) to 3 (positive). Additionally, semi-structured interviews were conducted post-experiment to gather users' opinions on the prototypes. Participants were individually queried about their likes and dislikes regarding the design. Semi-structured interviews were conducted post-experiment to gather users' opinions on the prototypes. Participants were individually asked to elaborate on their experiences. The example interview questions are "What do you like about the design?" and "What do you dislike about the design." The interview feedback was analyzed through thematic analysis [13] as introduced in the first iteration.

4.2 Results

4.2.1 Quantitative Results. An overview of descriptive statistics for physiological measures and self-reports on relaxation and anxiety

is depicted in Table 1 and Figure 5. Shapiro-Wilk tests revealed that the measures were not normally distributed in every condition. Therefore, Friedman tests and post hoc Wilcoxon signed-rank tests with Bonferroni Correction were utilized for statistical analysis.

Physiological Effects. A Friedman rank sum test revealed a significant effect on respiration rate ($\chi^2(2)=44.33$, $p < 0.001$) with a large Kendall's W effect size of 0.924. A post hoc Wilcoxon signed-rank test with a Bonferroni correction revealed a significant increase in respiration rate between the Baseline and Pre-PMR sessions ($Z = -3.928$, $p < 0.001$) with a large effect size of 0.801. This indicates that the stressful tasks significantly increased the breathing frequency, correlated to the increased excitement [10, 11], emphasizing the necessity of breathing regulation. A post hoc Wilcoxon signed-rank test with a Bonferroni correction revealed a significant reduction in respiration rate between the PMR and Pre-PMR sessions ($Z = 4.272$, $p < 0.001$) with a large effect size of 0.872. The respiration rate (Mdn = 6.25, SD = 0.50) matches the targeted frequency, indicating that the MindFlowV2 system effectively guided paced breathing during the PMR exercise. A post hoc power analysis confirmed that the sample size of $n = 24$ provided sufficient statistical power ($1 - \beta = 0.963$), indicating a 96.3% probability of correctly rejecting the null hypothesis given the observed effect size.

Subjective Relaxation and Anxiety. A Friedman rank sum test revealed a significant effect on RSS ($\chi^2(2)=25.364$, $p < 0.001$) with a large Kendall's W effect size of 0.528. A post hoc test using the A post hoc Wilcoxon signed-rank test with a Bonferroni correction revealed a significant increase in RSS between the Baseline and Pre-PMR sessions ($Z = 3.263$, $p = 0.001$) with a medium to large effect size of 0.666, indicating that the stressful tasks effectively reduced

Table 2: Results of User Experience Questionnaire (3: most positive; -3: most negative).

MindFlowV2	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
Mean (SD)	1.98 (0.64)	2.24 (0.63)	1.15 (0.52)	1.61 (0.66)	1.47 (0.79)	1.56 (0.90)

participants' subjective relaxation. A post hoc Wilcoxon signed-rank test with a Bonferroni correction also revealed significant increases in RRS between the Pre-PMR and the Post-PMR sessions ($Z = -3.867$, $p < 0.001$) with a large effect size of 0.789, demonstrating that the MindFlowV2 system effectively increased participants' subjective relaxation. A post hoc power analysis confirmed that the sample size of $n = 24$ provided sufficient statistical power ($1 - \beta = 0.920$), indicating a 92% probability of correctly rejecting the null hypothesis given the observed effect size.

A Friedman rank sum test revealed a significant effect on STAIS-5 ($\chi^2(2)=24.61$, $p < 0.001$) with a large Kendall's W effect size of 0.513. A post hoc Wilcoxon signed-rank test with a Bonferroni correction revealed a non-significant increase in STAIS-5 between the Baseline and Pre-PMR sessions ($Z = -1.797$, $p = 0.216$) with a small to medium effect size of 0.367, showing that the stressful tasks non-significantly increased participants' subjective anxiety. However, a post hoc Wilcoxon signed-rank test with a Bonferroni correction revealed a significant decrease in STAIS-5 between the Pre-PMR and the Post-PMR sessions ($Z = 4.094$, $p < 0.001$) with a large effect size of 0.836, indicating that MindFlowV2 effectively reduced participants' subjective anxiety. In the Post-PMR session, the users also reported a median STAIS-5 value of (SD = 1.062), which is the lowest possible score. A post hoc power analysis confirmed that the sample size of $n = 24$ provided sufficient statistical power ($1 - \beta = 0.947$), indicating a 94.7% probability of correctly rejecting the null hypothesis given the observed effect size.

User Experience Questionnaire. Table 2 depicts the UEQ results. The results reveal that MindFlowV2 receives positive evaluations (> 0.8) across all user experience aspects. According to the general benchmark based on 468 product evaluations [38], MindFlowV2 is excellent (top 10%) in attractiveness ($M = 1.98 > 1.84$) and perspicuity ($M = 2.24 > 2.00$), good (top 25%) in dependability ($M = 1.61 > 1.48$), stimulation ($M = 1.47 > 1.35$), and novelty ($M = 1.56 > 1.12$), and above average in efficiency ($M = 1.15 > 1.05$).

4.2.2 Qualitative Results from Interviews.

Immersive Experiences. Twenty-one participants (out of 24) mentioned that the virtual world helped them temporarily forget the stressful and distracting aspects of their daily lives, encouraging them to focus on relaxation training. Thirteen (out of 24) stated that the spatial environment created a calming and relaxing ambiance, triggering a sense of inner peace. For instance, participants mentioned, "The space, the galaxy, really helped me to reflect on my own... and I was almost asleep during the last few minutes." (P7) P5 also "The rich elements in VR make me feel curious." Participant P14 described the experiences as "floating in space". P6 and P23 mentioned it is easier to stay focused in VR.

PMR Guidance. Regarding PMR guidance, all participants stated that the animation of the 3D model was easy to understand for

muscle guidance. Additionally, 13 out of 24 participants mentioned that the self-avatar helped them connect with and feel their muscles, as participants expressed, "The self-avatar gave me a sense of connection between the virtual and reality" (P20) and "I became more interested in my hands and the instruction avatar and I think they better promote user engagement" (P21). P17 also mentioned, "To be able to see myself is very surprising." P24 remarks "Triggering the next step by making a fist and seeing the visual effects is intuitive and enjoyable." Also, 13 (out of 24) participants found the additional visual particle effects a useful cue, as participant P22 mentioned, "when the stars gathered around the (instructional) avatar, I wanted to tense my muscles. And when the stars spread out, I felt that the tension in my muscle was gone."

Participants also make suggestions for further improvements, such as making the pose instructions for forearm and biceps exercises less similar to each other (P12) and specifically instructing the users to put their hands down during relaxation so they know they do not have to lift their arms in front of the HMD all the time (P18).

Breathing Guidance and Feedback. All participants stated that the size changes of the guiding ball and their breathing ball in MindFlowV2 were easy to understand for breathing guidance. Participants described it as "intuitive and straightforward" (P15) and "providing a strong sense of guidance." (P22) Additionally, 11 (out of 24) participants stated that they were motivated to align the bubbles. For instance, participants described "I reached a state of Zen when I aligned them" (P8), and "matching them makes me happy and satisfied" (P17). Participant P12 further acknowledged the immersive graphics and mentioned "As I get more familiar with the breathing guidance, my attention shifted away from the bubbles. I start observing the starry sky in the background because I feel like I've entered the next level."

Nonetheless, 11 (out of 24) participants mentioned that the breathing guidance and feedback in MindFlowV2 sometimes pushed them too hard. For instance, participant P15 mentioned, "I feel I have to keep the cyan bubble at the center of the orange bubble" and "when I see the cyan bubble is not as large as that orange one, I feel I have to take extra breaths to match the size of that orange one." Participant P4 stated, "The edge of the two bubbles were obvious, so I wanted to match them perfectly. and then I focused more on the visuals." Regarding the size of bubbles, P19 also mentioned, "I tried to reach the exact size by breathing deeply and forcefully, but that prevents me from relaxing." Regarding the timing, participant P18 remarked, "I was like chasing the orange bubble, so I was not relaxed." Nonetheless, participant P9 found her way to accept the imperfection: "As I stopped trying too hard to synchronize my breathing with the bubbles, I began observing my surroundings stars and breathing with them. I realized I could also look at my hands. That is interesting."

5 Discussion

Overall, the findings support our hypothesis that incorporating an avatar can sustain the user's sense of presence and that a mindfulness-based design related to respiration and posture feedback can provide effective, breathing-integrated PMR guidance in VR. The results from the user study indicate that the 7-minute session, incorporating immersive and embodied upper-body PMR with breathing exercises, effectively guided novice users through their breathing and PMR exercises. Our quantitative results from a study involving 24 participants suggest that the system effectively enhances relaxation, reduces subjective anxiety, and attributes the virtual self-avatar and immersive environment to an attractive and stimulating experience. Their qualitative feedback also indicates that they could visually explore the *intimate correspondence* [26] between their bodily movements and the virtual space while sustaining their sense of presence in the virtual environment. They also found that the continuously updated virtual self-avatar increased their engagement and body movement awareness [53].

5.1 The Crucial Role of Full-Body Avatars in VR Mindfulness

Our study suggests that a full-body avatar in virtual reality (VR) is essential to create immersive and effective mindfulness applications by fostering a strong connection between physical and virtual users. By mirroring the movements and actions of users in real-time, the avatar promotes a sense of embodiment, where people perceive the avatar as an extension of their own body. This accurate reflection improves agency, enabling users to feel in control and deeply connected to their virtual environment. By visualizing their body and movements in VR, users can focus on bodily awareness, a key aspect of mindfulness. This connection is particularly impactful when integrated with natural interactions, such as breathing exercises, helping users stay engaged with their internal state.

Our study participants agreed that the immersive virtual environment and visual guidance were helpful. They also found that the continuously updated virtual self-avatar increased their engagement and body movement awareness [53]. Additionally, a full-body avatar creates continuity between the physical and virtual realms, reinforcing presence and minimizing cognitive dissonance. As users see their actions directly impact the virtual environment, they experience heightened control and realism, essential for maintaining motivation and emotional engagement.

5.2 Designing Virtual Avatars for Immersive Mindful Interaction

Proper design of virtual avatars in bodily exercise (e.g., breathing-integrated PMR) in VR is essential for creating an immersive, engaging, and effective user experience in mindfulness-based applications. A critical factor is the reduction of inconsistencies between the user's physical actions and the virtual representation of the avatar. When these inconsistencies occur, they disrupt the sense of presence, making users acutely aware of the virtual nature of the environment. This awareness undermines the feeling of *being there*, which is vital for fostering immersion.

Moreover, improperly designed avatars can make users feel disconnected from their virtual bodies. This disconnect reduces the

perceived realism of the experience, making it less engaging and less likely to sustain user interest, as users may struggle to see the intuitive link between their actions and outcomes. For instance, in the first iteration of MindFlow, some participants found the appearance of their avatar visually unpleasant, and the movement of the avatar towards and away from them to be distracting and felt like an *out-of-body experience*. Such misalignment also increases cognitive load, forcing users to consciously adjust to the discrepancies between their physical actions and the avatar's responses. This added mental effort distracts from their focus and enjoyment. Additionally, negative emotional responses such as frustration or unease can arise when the experience feels disjointed, counteracting the potential therapeutic benefits.

Subtle design choices in virtual avatars play a pivotal role in the success of VR experiences, especially in mind-body exercises. Avoiding overly detailed avatars ensures that users remain focused on their internal sensations rather than external aesthetics [20]. For instance, the second iteration of MindFlow employed a minimalist monochrome avatar, promoting awareness of muscle movement and bodily engagement. Furthermore, integrating natural interaction methods like breathing enhances the connection between the user and their avatar, fostering a deeper sense of presence and immersion. Ultimately, the alignment between physical actions and virtual representation is vital for creating intuitive, engaging, and therapeutic experiences in VR.

5.3 Biofeedback as a Meaningful Background for Mindful Interactions

Respiration biofeedback creates a continuous loop that can increase users' awareness of their bodily sensations, promoting a deeper connection between the mind and body. This constant interaction helps to keep users aware of their breathing without being intrusive, and provides users with the necessary information to understand and self-regulate their breathing. Our finding is in line with previous work [67, 83] as they suggest (bio-)feedback should be designed as a meaningful *background* for mindful interactions (R2). The results of the user study show that both the guidance and breathing feedback were clearly provided. Nonetheless, findings also revealed tensions between providing clarity in instruction (R1) and promoting acceptance without judgment or striving (R3), as the users of MindFlowV2 were intrinsically motivated to achieve the best performance when the guidance was too strong. Meanwhile, the non-judgmental respiration feedback encourages users to observe their experiences rather than conforming to strict rules. For instance, although some participants felt that the system occasionally pushed too hard and caused distress when they could not match the bubble exactly, some decided to embrace imperfection. Given VR's capacity for immersive visualization, as seen with participants' positive responses to effects like the moving stars, we recommend *leveraging immersive visualization in the background to optimize biofeedback visualization experiences and biofeedback as a presence-with experience* [83] in future design iterations.

5.4 Designing Virtual Environments to Enhance Embodied Mindfulness

The design of virtual environments in VR mindfulness applications plays a crucial role in enhancing user engagement and relaxation while supporting therapeutic goals. By integrating goals and visual elements into the environment, breathing exercises can become immersive and enjoyable. For instance, Stairway to Heaven [50] uses a virtual wilderness to transform breathing into a journey-like experience that concludes with a visual overview for reflection, increasing motivation and helping users focus on their breath through visual cues that align with their breathing patterns.

Virtual environments based on nature, such as forests or underwater scenes, promote relaxation and reduce stress. According to Attention Restoration Theory (ART) [32], spending time in nature provides mental health benefits, including improved focus and reduced stress. By simulating natural settings, VR can replicate these restorative effects, making the environment a calming and therapeutic space for mindfulness practices.

Dynamic and adaptive virtual environments further enhance the user experience by responding to individual breathing patterns in real time. This personalization deepens engagement and aligns the virtual experience with the user's internal state. Additionally, incorporating embodied interaction with the self-avatar strengthens the connection between the user's physical sensations and the virtual world, which is critical for body-based mindfulness practices [22]. Overall, thoughtfully designed virtual environments not only provide calming spaces but also actively guide and support mindfulness practices, making them powerful tools for mental and physical well-being.

5.5 Designing Embodied Mindfulness in Mixed Reality

Being in familiar environments still evokes a sense of safety for people. Immersive experiences can be achieved when users control their surroundings, for example, adjusting lighting or creating a cozier atmosphere. Figure 6 illustrates our latest implementation on a Meta Quest 3 HMD with an enhanced colorful pass-through mode, surpassing earlier iterations by incorporating features like colored see-through mode and virtual hand tracking that resembles a glove for the user. This development could serve as a promising starting point for exploring new avenues in *hybrid self-avatar* in mixed reality. Such exploration could offer improved support for tangible interactions involving physical self-regulation [43] compared to having a virtual self in a purely VR environment (R4). Advanced HMDs with even higher visual fidelity and gaze tracking, such as Apple Vision Pro and Oculus Quest Pro headsets, can facilitate further customization of blended environments and leveraging voluntary gaze-based interactions, which could provide opportunities for *promoting autonomy* [64] for more experienced users.

5.6 Limitations and Future Work

Technical Design. Researchers may consider the potential of enhancing the system to offer comprehensive tracking experiences for the entire body or muscle activity by incorporating highly responsive and accurate equipment, leveraging the state-of-the-art machine learning framework to learn to map the user's posture

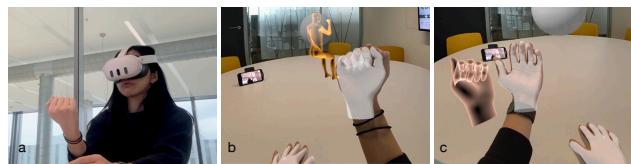


Figure 6: Hybrid self-avatar: a) User wearing a Meta Quest 3 HMD; b) Engaging with the MindFlow program in a familiar environment, with her hand-tracking models visualized as virtual gloves; c) Following nearby guidance.

from the HMD's pose and camera input to control a full-body avatar in real-time [46], and exploring contactless respiration and heart rate sensing techniques based on radar [1] can reduce the need for wearing a breathing sensing belt. These extensions could facilitate mind-body practices beyond upper-body breathing-integrated PMR exercises alone and encompass various additional biofeedback modalities, such as mixed-reality exergames [33].

We recommend future research in this direction and minimizing the requirement for additional cameras and sensors to retain the potential for field deployment of this relaxation system over an extended period. On the other hand, we invite future exploration of the design with virtual objects and others following the guidelines proposed by Döllinger et al. [22], to provide additional motivations for the PMR integrated with upper body breathing for users to maintain their practices long term.

Study Design. Our approach demonstrates the effectiveness of using conventional hardware to provide body-based exercises and breathing-integrated PMR, which can help novice PMR users cope with acute stressors (e.g., the Stroop color-word test). Since the cost of HMD and wireless breathing belts at this hardware specification has been made affordable, future research can continue the path to deploy the system at a larger scale with a longitudinal field test to understand how users sustain the learned skills and use them to cope with their daily stressors and chronic anxiety.

Our study does not yet include a control group because it focuses on addressing specific technical and design challenges rather than broad applicability or comparative validation. At this stage, the primary goal is to demonstrate proof of concept by confirming the idea works under specific conditions. Incorporating a control group prematurely could lead to inefficiencies, as the concept is still undergoing iterative refinement and development. By prioritizing the exploration of feasibility and foundational aspects, we aim to establish the innovation's core value first, ensuring a solid foundation before progressing to broader validation, such as the inclusion of a control group.

Future work can further explore the design space by isolating specific design elements and evaluating their impact on users' sense of presence, as well as investigating long-term engagement by examining whether users continue using MindFlow over time. Key research questions include how its effectiveness evolves with repeated use, whether users lose interest in the biofeedback visualizations, or if they find the structured guidance too rigid. Furthermore, exploring how user participation in perspective selection and visual feedback representation customization may inform the design of

more personalized and effective biofeedback systems [42]. Future studies could also examine how improving instructional clarity and embodied presence, enabling users to seamlessly switch between observing guided movements and experiencing them through their virtual self-avatar, could enhance adherence in the long term.

6 Conclusion

We have introduced a design approach that incorporates a full-body avatar to sustain the user's sense of presence and employs mindfulness-based principles related to respiration and posture feedback to provide effective, breathing-integrated PMR guidance in VR. By utilizing a commodity HMD and minimal sensor instrumentation, *MindFlow* addresses a gap in prior work by offering an embodied mindfulness experience in an immersive environment that integrates breathing-based biofeedback with full-body self-avatars to enhance presence, guidance, and the effectiveness of progressive muscle relaxation. *MindFlow* contributes a system design that demonstrates effectiveness in enhancing relaxation and reducing anxiety in novice users, based on empirical results from a 24-participant user study. Specifically, its main contribution lies in the design and evaluation of an integrated system that effectively induces relaxation and alleviates anxiety. Study results suggest that the system not only enhances relaxation and reduces subjective anxiety but also attributes the full-body self-avatar and immersive environment to an engaging and stimulating experience. Our empirical findings offer generalizable insights for the design of embodied mindfulness systems and inform further research on supporting mindfulness in virtual or mixed reality. This includes guidance on leveraging immersive background visualization to optimize biofeedback experiences and lays a foundation for future empirical studies and technical developments aimed at advancing mental health and well-being through embodied mindfulness.

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