CoBreath: Designing a VR-Based Dyadic Biofeedback System to Support Breathing Exercise for Breast Cancer Survivors

Qi Wang
College of Design and Innovation
Tongji University
Shanghai, China
qiwangdesign@tongji.edu.cn

Yifan Yan
College of Design and Innovation
Tongji University
Shanghai, China
yifanyan@tongji.edu.cn

Shiwen Fang
College of Design and Innovation
Tongji University
Shanghai, China
shiwen19981208@163.com

Qingfan An
Umeå University
Umeå, Sweden
qingfan.an@umu.se

Xiujia Luo
Shanghai University of Sport
Shanghai, China
luoxiujia0623@163.com

Jie Jia*
Huashan Hospital Fudan University
Shanghai, China
shannonjj@126.com

Bin Yu*
Digital Life Group, Faculty of Digital Media and Creative Industries
Amsterdam University of Applied Sciences
Amsterdam, Netherlands
b.yu@hva.nl

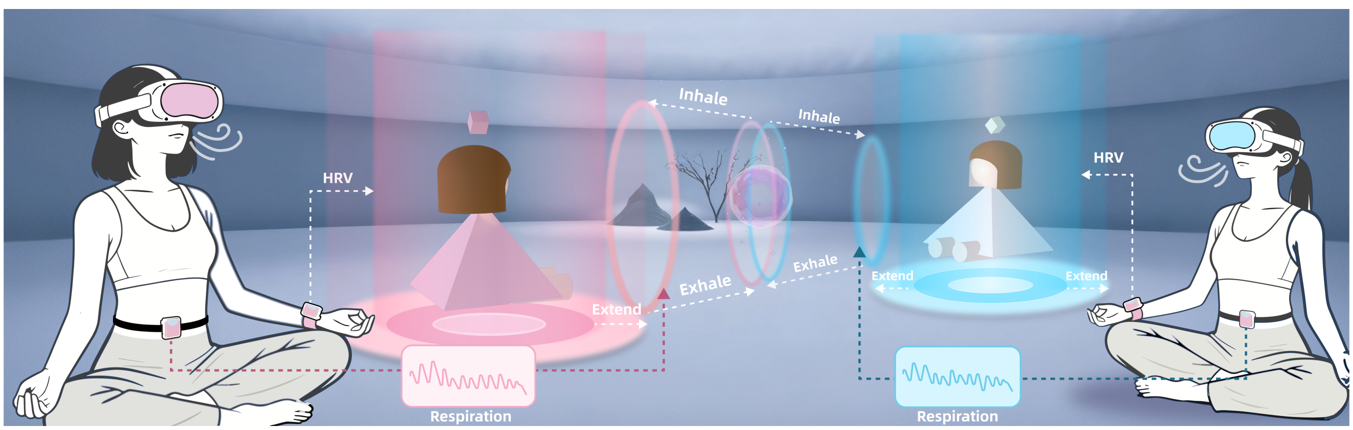

Figure 1: We present *CoBreath* , a dyadic VR biofeedback system for breast cancer survivors to practice paced breathing for relaxation. A fabric respiration belt and a wrist-worn HRV sensor capture users' breathing and HRV signals. Within a calming VR environment, each partner's breathing drives the movement of their *light field* and *halo ring*, while HRV modulates the color, creating a shared, non-competitive relaxation experience with a peer or family member.

Abstract

Chronic stress and anxiety severely affect breast cancer survivors' (BCSs) mental health and well-being. Peer support has been shown to enhance psychological empowerment, while biofeedback offers a promising approach to improve physiological relaxation through self-regulation. However, few studies explored combining both for BCSs. We conducted a formative study with clinicians and BCSs to identify requirements and preferences for VR biofeedback. Informed by the findings, we proposed a VR-based dyadic biofeedback system, *Cobreath*, which integrates breathing and heart rate variability (HRV) feedback into a calming virtual environment, allowing two users to practice breathing-focused relaxation simultaneously. Through a clinical user study with ten clinicians and a between-subjects study with 32 BCSs, we demonstrated that *Cobreath*'s dyadic mode improved biofeedback effectiveness and provided a better user experience compared to the individual mode. We further

*Corresponding author.

CHI '26, Barcelona, Spain

ACM ISBN 979-8-4007-2278-3/26/04
https://doi.org/10.1145/3772318.3791096

discuss insights and design considerations for developing dyadic VR-biofeedback applications to support the mental well-being of BCSs and potential applications.

CCS Concepts

• **Human-centered computing → Interactive systems and tools**.

Keywords

Biofeedback, Virtual Reality, Paced Breathing, Breast cancer survivors, Dyadic interaction

ACM Reference Format:

Qi Wang, Yifan Yan, Shiwen Fang, Qingfan An, Xiujia Luo, Jie Jia, and Bin Yu. 2026. CoBreath: Designing a VR-Based Dyadic Biofeedback System to Support Breathing Exercise for Breast Cancer Survivors. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems (CHI '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 20 pages. https://doi.org/10.1145/3772318.3791096

1 Introduction

Breast cancer is the most commonly diagnosed cancer and the second most common cancer globally, posing a major public health concern due to its high incidence and mortality rates [115]. Although breast cancer predominantly affects women, it can also occur in men and individuals of other gender identities[21]. During the post-treatment recovery, breast cancer survivors (BCSs) often report a range of psychosomatic symptoms, including fatigue, pain, and physical discomfort long after treatment has ended [73]. Besides the treatment's side effects, chronic stress has been shown to be a serious psychological burden [12, 15] and one of the major causes to psychosomatic symptoms [73]. Numerous studies [44, 59, 68, 118] also highlight the urgent need to provide comprehensive support and develop new interventions to help BCSs cope with stress and improve their quality of life.

Relaxation training with slow-paced breathing is a widely used intervention for reducing anxiety and enhancing well-being[6]. It has been shown to be effective in stress management among students [101], young adults [126], older adults [65], and patients with anxiety disorders [98]. In particular, a clinical study with 322 post-treatment BCSs showed that a six-week, psychologist-led relaxation training program significantly improved psychological outcomes and fatigue-related symptoms, with benefits sustained over 6 to 12 weeks [88]. To improve stress reduction outcomes, the biofeedback (BF) technique is increasingly integrated into relaxation training to help individuals better understand their physiological states and gain more control over stress responses through real-time sensor feedback[13, 111].

Biofeedback [31] facilitates users to regulate physiological states and processes through real-time sensor feedback. As a stress management tool [53, 119], biofeedback has been widely applied across domains such as sports, cognitive performance, chronic pain, headaches, anxiety, and depression [61, 80, 100, 110], and more recently for managing physical symptoms among cancer survivors [36]. Although effective in supporting stress reduction, traditional BF systems that rely on standard graphical interfaces within clinical settings often result in low user engagement and suboptimal relaxation outcomes [78, 114]. To overcome this limitation, growing research in HCI has explored the use of Virtual Reality (VR) in biofeedback to support a calming and engaging user experience.

VR-based biofeedback (VR-BF) [69] has demonstrated improvements in concentration, engagement, and the meditative experience. Rather than interpreting abstract graphs, users can perceive their physiological states and changes through multimodal stimuli within immersive virtual environments. For instance, *Forestlight* [123] employs interactive lighting in a virtual forest environment to provide feedback, guiding users to take deep breaths for stress relief. *DEEP* [112] embeds biofeedback into a VR game, allowing children to relax in a virtual underwater world and to learn anxiety regulation skills. A recent design *MindFlow* [117] integrates breathing-based biofeedback with a full-body self-avatar in VR to enhance presence, guidance, and effectiveness in progressive muscle relaxation. Although various VR-BF systems have been developed, few have yet been specifically designed for BCSs who often face persistent clusters of fatigue, pain, and anxiety arising from treatment-related side effects and heightened fear of recurrence. These psychosomatic and psychosocial vulnerabilities of BCSs necessitate new relaxation tools that are emotionally safe, low in physical demand, and engaging for long-term use.

Notably, research indicates that 52% of cancer patients prefer one-on-one peer support [10, 45]. Prior studies [22, 128, 128] suggest dyadic support between cancer survivors reduces depressive symptoms and anxiety, and increases psychological empowerment and quality of life. Among breast cancer patients, one-on-one face-to-face peer support was shown to be effective in improving self-efficacy and self-management [60]. Peer support and shared experiences have also been incorporated into relaxation training to enhance user engagement. For instance, a personal-disclosure mutual-sharing approach was developed to enhance cohesion in team-based mindfulness meditation programs [85]. Mindfulness-based group interventions have shown promise in reducing anxiety, avoidance, and fear of cancer recurrence among prostate cancer survivors [17] and adolescents with cardiac conditions [32]. HCI technologies have broadened access to peer-supported and group-based relaxation training, for instance, through video conferencing [18], livestreaming[64], VR meditation games [66], social biofeedback systems [47, 104]. Despite these benefits, few studies have examined the integration of peer support and biofeedback within an embodied VR environment for relaxation training. To address this gap, the present study investigates the design of a VR-based dyadic biofeedback system for BCSs and examines the following research questions:

- **RQ1:** What are the key design requirements for a VR-BF system to effectively support relaxation training among BCSs?
- **RQ2:** How can a dyadic biofeedback interaction be designed in VR to facilitate the co-practice of paced breathing and enhance shared stress-relief experiences?
- **RQ3:** How do therapists and physicians perceive the *CoBreath* VR-BF system in terms of feasibility and its potential as a relaxation tool for BCSs?

- **RQ4:** To what extent is the *CoBreath* VR-BF system effective in supporting relaxation training, and what are the differences in effectiveness and user experience between the dyadic and individual modes?

The structure of the study is illustrated in Fig. 2. To answer these RQs, we first conducted a formative study with clinicians, mindfulness specialists, and BCSs who experience psychosomatic symptoms to define the design requirements for a VR-BF system tailored to BCSs (RQ1). Using semi-structured interviews and a user survey, we engaged participants in exploring design opportunities and how VR and biofeedback could better facilitate relaxation training. The findings revealed that BCSs prefer VR-BF systems that provide an embodied mindfulness experience, a dyadic biofeedback interaction, and a breathing-focused relaxation practice (RQ1). Based on these findings, we designed and implemented *CoBreath*, a VR-based dyadic biofeedback system which integrates breathing and heart rate variability (HRV) feedback into a calming virtual environment and allows two users to practice breathing-focused relaxation simultaneously. We present the design considerations and processes answering the second research question (RQ2).

Next, we conducted a clinical user study with 10 clinicians and therapists to validate the credibility and usability of *CoBreath* from a clinical perspective. Results showed that *CoBreath* was perceived as 'excellent' in the usability scale and met clinicians' expectations (RQ3). We then conducted a field deployment study with 32 BCSs to investigate the system's effectiveness, usability, and user experience. Using a between-group experimental design, we compared the individual and dyadic modes of biofeedback during a 10-minute relaxation training session. The results showed that the dyadic mode led to a greater increase in HRV and provided a better user experience compared to the individual mode (RQ4). We then further discussed insights and design considerations for future VR-BF systems like *CoBreath*.

The contributions of this work are as follows: 1) *CoBreath*, a VR-based dyadic biofeedback system that supports peer-assisted breathing exercise for stress reduction among BCSs in post-treatment care; 2) A clinical evaluation study in which each participant experienced both individual and dyadic modes of the *CoBreath* system and then assessed its credibility and usability for relaxation training; 3) A field-deployed between-subjects study with 32 BCSs demonstrating the effectiveness of dyadic biofeedback in enhancing stress reduction outcomes and user experience compared with the individual mode; 4) Rich empirical insights and design considerations to guide the future development of VR-BFsystems aimed at supporting post-cancer stress management and mental wellbeing.

2 Related Work

2.1 Psychosomatic Symptoms and Chronic Stress among Breast Cancer Survivors

Breast cancer patients often experience both physical and psychological stress [24] during the disease process and treatment, often accompanied by somatic symptoms that are difficult to fully explain through medical means. Patients commonly experience physical complications, including upper limb dysfunction [74], joint discomfort, sleep disturbances, and chronic pain. Physiological changes associated with breast cancer and its treatment can trigger significant stress responses, leading patients to experience various psychological sequelae, including somatic symptoms [63], anxiety [12], depression, altered body image [109], and identity disruption. This heightened emotional distress and diminished quality of life may subsequently compromise treatment adherence and negatively impact disease outcomes [24].

To address post-treatment psychosomatic symptoms in BCSs, various therapeutic approaches [19] have been developed, including cognitive behavior therapy [83], mindfulness-based interventions [124], and breathing training techniques [20]. Among these interventions, breathing training techniques have emerged as a notably promising and accessible way due to their ease of implementation, cost-effectiveness, and minimal side effects. Recent studies [29] have demonstrated the effectiveness of breathing exercise on stress and mental health; similar benefits have also been observed in cancer-related stress cross various populations [16]. A recent review [35] involving 1,726 breast cancer patients confirmed positive outcomes in quality of life and emotional well-being through various breathing interventions, while simultaneously identifying the challenges of increasing the accessibility of the intervention, enhancing adherence through wearable device and improving satisfaction, etc. Recently, researchers have applied emerging technologies to leverage the breathing intervention [8, 86, 87] in cancer survivor populations. However, the application of these technological innovations specifically within breast cancer care remains limited, representing a significant gap in digital interventions for this population.

2.2 VR Biofeedback for Stress Management and Relaxation Training

Biofeedback is a mind-body technique that has been widely used to facilitate stress reduction through self-regulation [31]. Typical biofeedback systems measure an individual's physiological signals and transform them into visual or auditory feedback, typically displayed on a monitor with therapist guidance. These systems are generally designed for single-user scenarios [95]. Subsequently, participants get insight into their internal physiological processes and use this feedback to promote healthier regulation of their physiology [31]. Biofeedback has shown effectiveness in facilitating breathing exercises and stress management, promoting autonomic balance associated with relaxation [37, 53, 119]. Respiration and heart rate variability (HRV) are the most commonly used physiological data in biofeedback-assisted relaxation [57, 62]. Slow-paced breathing is commonly employed as a key self-regulation component in relaxation training [7, 72, 90]. It could effectively reduces sympathetic arousal and increases parasympathetic nervous system (PNS) activity [122]. HRV reflects beat-to-beat fluctuations in heart rate that are largely driven by PNS activity [106], therefore, higher short-term HRV is generally associated with improved autonomic balance and a relaxed, recovery-oriented state [96]. Therefore, time-domain HRV indices such as the root mean square of successive differences (RMSSD) are commonly used in biofeedback studies as robust indicators of improved relaxation outcomes [58]. Respiration and HRV biofeedback systems have been shown to be

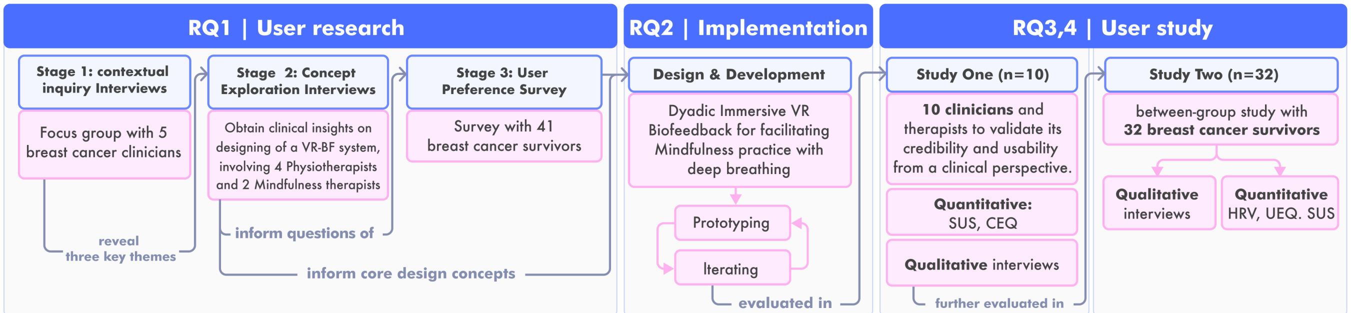

Figure 2: The overall structure of the paper.

effective for stress reduction across diverse groups, including pregnant women [116], children and adolescents [27], veterans [94], and older adults [50]. They has also been increasingly applied in cancer care [38, 81, 102], particularly among patients with breast cancer [25, 71]. However, most studies have primarily focused on evaluating the efficacy of traditional biofeedback devices, with limited research addressing the design of novel biofeedback systems and experiences tailored to the specific needs and preferences of BCSs.

Much HCI research has investigated using VR in newly developed biofeedback systems to enhance their effectiveness and user experience [26, 56, 69]. VR immerses users in controlled, multisensory environments that minimise distractions and allow them to focus fully on relaxation techniques, such as mindful breathing exercises [9, 82, 84]. By fostering a strong *sense of presence*, VR systems effectively enhance the depth and quality of the relaxation experience [113]. By synchronizing dynamic changes in VR elements (visual or auditory) with users' real-time physiological data, the VR environment becomes an immersive biofeedback interface that delivers feedback and supports self-regulation [7]. In HCI, various VR biofeedback systems have been developed. For instance, *Forestlight* biofeedback system maps users' respiration data with lighting in a virtual forest environment to facilitate breathing exercises and reduce stress [123]. *DEEP* [112] virtual game was designed to help children manage anxiety with respiration biofeedback displayed in a virtual underwater world. *MindFlow* [117] combines breathing biofeedback with a full-body self-avatar, providing breathing-integrated relaxation guidance in VR. Some research has integrated biofeedback-based breathing exercises into a more playful VR game to enhance users' engagement. For instance, *BreathVR* uses the user's breathing as a direct control for visual effects in VR game [103]. *InnerGarden* [91] represents users' breathing and HRV in a mixed reality virtual world. A more recent example is *Stairway to Heaven*, which offers users a gamified VR journey to cultivate mindful awareness of breathing [76]. However, among those existing VR breathing and mindfulness systems, few address the specific user experience needs of BCSs, and most are designed for single-user interaction. Given that dyadic practice with peer support can help survivors feel less isolated and more emotionally supported during training, our design of *CoBreath* emphasizes and investigates this feature.

2.3 Peer Support in Stress Management and Relaxation Training

Peer support is a person-centred approach in which individuals with relevant lived experience provide emotional, informational, appraisal, and practical support to others in comparable circumstances [22]. It is widely used in cancer survivorship and rehabilitation [4, 54], mental health care [97], relaxation training programs [1, 77], and chronic diseases management [49]. In oncology, peer support has been associated with improvements in active coping of anxiety [125], managing fear of cancer recurrence [89, 107] and quality-of-life gains among BCSs [43]. By participant count, peer support is commonly delivered in dyadic (one-to-one) or group-based formats (3-12 participants) [41] in person or digitally. HCI technologies and designs have addressed peer support and multi-user interactions in the context of stress management. For example, *heartchat* uses heart-rate–augmented messaging to enhance social connection [40]. *DYNECOM* augments meditation with multi-user respiration and EEG biofeedback, visualizing dyadic synchrony to boost physiological synchrony and empathy [48]. *ComPeer* proactively delivers LLM-driven peer support by detecting salient events and timing outreach to sustain engagement and reduce stress [67]. However, most systems are framed around everyday communication, entertainment, or generic wellbeing rather than post-treatment care. Little research has been conducted on investigating peer support in paced breathing relaxation training, especially BCSs. This gap motivates our design of dyadic biofeedback.

3 Formative Study

As shown in Fig. 3, to ground the design and implementation of *CoBreath*, we conducted a three-stage user and context research: (1)semi-structured interviews with five breast cancer clinicians to explore current clinical solutions for psychosomatic symptoms and expectations for stress management; (2)co-creation sessions involving three clinicians and two mindfulness therapists to identify design opportunities and generate initial concepts of *CoBreath*; (3) and a user preference survey with 41 BCSs to understand their preferences and needs regarding VR-based relaxation training. All three stages of the formative study were approved by the Ethics Committee of Tianjin Medical University Cancer Institute and Hospital (approval number: bc20241747). All participants received an information sheet describing the study aims and procedures and provided written informed consent, including consent for the anonymized use of their interview data or survey results in publications.

3.1 Stage 1: Contextual inquiry Interviews

In Stage 1, we first conducted semi-structured interviews with five clinicians. Their details are presented in Table 1. The interview aimed to gain information on three topics: (1) current post-treatment care and home-based recovery for BCSs; (2) recommended relaxation techniques to address somatic symptoms among BCSs; and (3) clinical requirements and expectations regarding VR and biofeedback technologies for relaxation training. The detailed interview guide and questions are provided in the supplementary materials. The interviews (~40 minutes each) were conducted in person or via video-conference, recorded with the consent of the participants. Regarding the interview data analysis, we adopted an inductive, ground-theory-inspired approach [105]. Two authors first independently read all transcripts to familiarize themselves with the material and then conducted an *open coding* process, in which meaningful segments of text were extracted and assigned initial codes. Next, through *axial coding*, similar or related codes were grouped into conceptual categories, forming the primary coding structure. The authors then met to compare and refine their coding schemes, discussing discrepancies until consensus was reached. Finally, in a *selective coding* step, we analyzed relationships among categories and organized them into broader themes.

Results Our analysis revealed three key themes shaping the design space of a VR-based biofeedback system for supporting relaxation training and stress reduction among BCSs:

- **Design for long-term, home-based post-treatment rehabilitation.** Clinicians described post-operative recovery as predominantly home-based with supplementary outpatient sessions. Rehabilitation is *"long-term"* and *"progressive"*. Patients need a clear, actionable daily routine and emotional support. As PS1 noted, *"Somatic symptom disorders are primarily managed through non-pharmacological approaches such as cognitive behavioral therapy, and tools and systems specifically designed for long-term home use by cancer survivors remain limited"*. Current stress interventions often rely on generic audio guidance or video materials, leading to low adherence and inconsistent quality. For instance, PT3 stated that *"We might use a pre-recorded mindfulness track... so patients can practice at home. But there are obstacles, such as their adherence is normally low, and the relaxation practices in the home environment are often easily disturbed or distracted."* In addition, PT2 stated: *"many hospitals offer regular group classes to guide BCSs through relaxation and mindfulness exercises, which have been well received."* Yet staffing shortages often interrupt clinic-run relaxation training sessions and mindfulness classes: *"relaxation training programs such as mindfulness classes in many clinics are often discontinued, not due to lack of value, but because staff are overwhelmed with daily tasks and can't maintain them consistently."* (PH1) There is a growing need for technology-assisted, home-based relaxation training programs that BCSs can use at home and integrate into their daily routines.
- **Address symptom clusters via companion assistance and peer support.** Sleep disturbance, fatigue, and pain frequently co-occur and are amplified by anxiety, especially perioperatively and during chemotherapy. PS1 emphasized that *"mutual support among survivors, for example, having a rehabilitation partner to practice together, or daily check-ins and exchanges in peer WeChat groups could be helpful in easing feelings of isolation and providing an emotional sense of being understood."* PT2 further noted that when family members accompany patients in relaxation training and co-establish regular daily routines, patients are more likely to maintain a stable practice. Moreover, PH1 emphasized that *redirecting attention towards constructive activities can alleviate sleep disturbance and fatigue.* They also highlighted the importance of *emotion regulation*, such as PT2 stated that *"a breast cancer patient started knitting small plush items every day. It gave her a positive feeling—she put her energy into it and stopped ruminating.* Together, these results motivate designs that pair *companion assistance* scaffolds with *emotion-regulation* to alleviate symptoms and sustain practice.
- **Design intuitive VR and biofeedback experiences.** The participating physiotherapists were optimistic about the combination of VR technology and biofeedback. But they also emphasized that the usage and user experience of such a VR-based biofeedback system should be *simple*, *easy-to-learn*, and *low cognitive load.* And interaction mechanics should remain straightforward. For instance, PH1 suggested *"keep it simple, don't make the interactions too complicated"*. Clinicians also noted that factors such as age and educational background influence how readily patients accept new technologies (PT3), underscoring the need for accessible and intuitive interfaces. They also suggested incorporating features such as *progressive difficulty*, *moderate rewards*, and *peer-support co-practice* to enhance motivation for long-term use.

Taken together, these three themes outline the design space and its key components for VR-based biofeedback from a clinical perspective. The clinicians highlighted the need for tools that are both clinically grounded and practical for long-term, home-based BCS rehabilitation, the value of social connection and peer support in managing post-treatment anxiety and symptom clusters, and the importance of simple, low-demand VR and biofeedback interfaces and experiences. In the next stage, we further incorporated these insights into the concept development process.

3.2 Stage 2: Concept Exploration Interviews

In Stage 2, we further explored the design space outlined in Stage 1 by translating the key themes reflecting clinicians' needs into concrete system concepts and interaction features for *CoBreath* .

Participants and Procedures. To develop the core features of *CoBreath* , we conducted two concept exploration sessions: one with four physiotherapists (PT1, PT4, PT5, and PT6) and one with two certified therapists (TH1, TH2). Each group session lasted approximately 40 minutes and followed the same procedure. Among them, PT1 had previously participated in the Stage 1 interview,

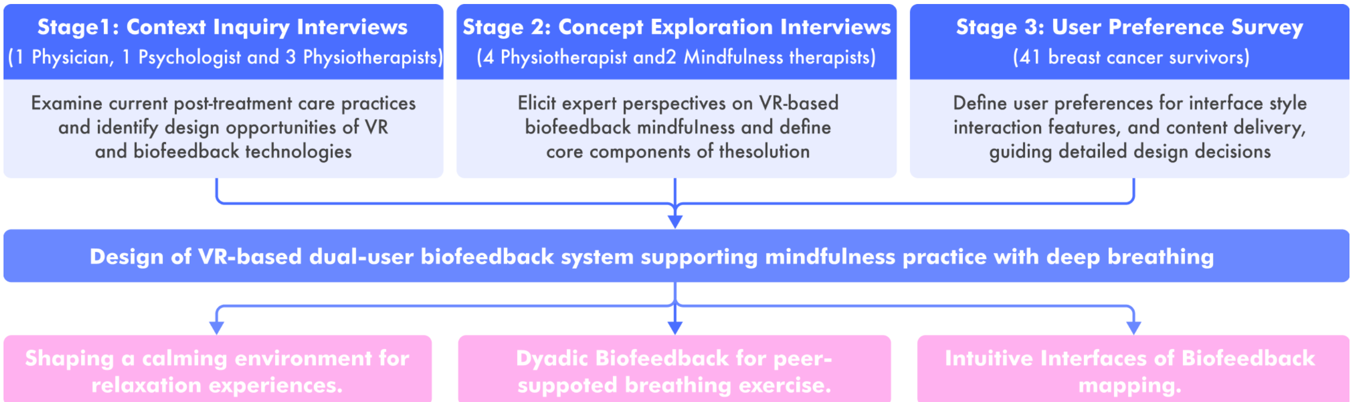

Figure 3: The three stages of formative study and the design goals of *CoBreath*.

Table 1: Basic information of participants in contextual inquiry interviews. *Note.* PT1 also participated in the concept exploration interviews in Stage 2.

Profession	Clinical expertise	Years of experience
Physician (PH1)	Rehabilitation Medicine / Stroke Rehabilitation and Cancer Rehabilitation	39
Psychologist (PS1)	Psycho-oncology	15
Physiotherapist 1 (PT1)	Somatic symptoms rehab	2
Physiotherapist 2 (PT2)	Upper-limb rehab	32
Physiotherapist 3 (PT3)	Lymphedema rehab	8

whereas the other five participants were newly recruited. Participants' details are shown in Table 2 and the interview guides are provided in the supplementary materials. Each concept exploration session began with a brief introduction to the project, followed by a discussion of the envisioned role of VR-based biofeedback in BCS relaxation training, and concluded with a brainstorming activity to stimulate participants' creativity. For the brainstorming part, we presented four examples of recently developed VR-based biofeedback relaxation systems (see supplementary material for details). We outlined each design's objective, interaction technique, and application scenario. We explicitly framed these four systems as non-exhaustive design probes rather than templates to follow, and encouraged participants to "go beyond" them when imagining new concepts. The participants used the 'Crazy-8s' exercise [39] to sketch individually on their own worksheet, considering four aspects: *device form*, *interaction modality*, *embodiment of biofeedback display*, and *potential application scenarios*. After finishing sketches, participants verbally presented and discussed their concepts with the interviewer.

Data Analysis and Results. With participants' consent, the discussions around the probes and the concepts they generated were audio-recorded and transcribed verbatim. The sketches themselves were collected (photographed and digitised) and analysed together with the transcripts and researchers' field notes. We then conducted an inductive thematic analysis [11] focusing on recurring design concepts and features. Two authors independently coded the material, compared and refined their codes through discussion, and iteratively clustered them into higher-level themes. This analysis yielded four design features that should be included in the core concept of *CoBreath* :

- **Direct users' attention to their body and breath.** This concept aims to create a simple, *non-game-like virtual environment* to support present-moment focus and interoceptive awareness. As PT1 put it, *"The goal is to keep users' attention focused on the present and their body. So if we're designing something new, we probably shouldn't create complex game-like scenarios. The (VR) environment should be simple and pure."* They also highlight the importance of using VR or simple physical objects (e.g., a ball or sleeve) to *"deepen sensory engagement"*.
- **Support deep breathing regulation in relaxation.** Experts recommend using *paced breathing* and pairing it with *gentle, easy-to-follow body movement* to reduce tension and anxiety while addressing bodily fatigue. The system should provide patients with pacing cues in a calming way, to help them learning breathing skills but also feel relaxed. As PT4 suggested *"we should provide support, like simple guidance for deep breathing exercises and maybe combining slow body movement. Deep breathing practice can help patients relax, focus on the present, and reduce stress—especially when done in a calm, consistent routine at home."*

Table 2: Basic information of participants in concept exploration interviews

Profession	Clinical expertise	Years of experience
Physiotherapist 1 (PT1)	Rehabilitation of somatic symptom disorders and sleep disturbance in breast cancer	2
Physiotherapist 4 (PT4)	Cognitive impairment rehabilitation	2
Physiotherapist 5 (PT5)	Lymphedema rehabilitation	1
Physiotherapist 6 (PT6)	Upper-limb dysfunction rehabilitation in breast cancer	4
Therapist 1 (TH1)	Relaxation Instructor Trainer	4
Therapist 2 (TH2)	Relaxation Teacher-Training Supervisor; extensive experience in cancer immunology research	11

- **Peer support and companionship in daily practice.** Extending the Stage 1 insight that social connection and companionship are important for BCSs managing symptom clusters, physiotherapists proposed concrete ways of weaving peer support into patients' routines. They highlighted that *emotional companionship* may support patients in overcoming setbacks encountered during their daily practice routines and sustain adherence through *gentle accountability*. PT6 noted that *"they can reinforce each other, by joining in pairs, they could have mutual reminders, peer-to-peer prompts"*. Such *social companionship scaffolds* were seen as especially valuable amid post-treatment anxiety.
- **Support dyadic biofeedback to enhance engagement.** Physiotherapists suggested design concepts that enable two users to engage with biofeedback in the same session. This would allow the users to practice deep breathing together. As TH1 suggested *"When two people participate together, whether it's patient and therapist, or patient and companion, they can see each other's progress in real time, encourage one another, and make the experience more interactive and motivating"*. Crucially, this dyadic mode should be framed as collaborative rather than competitive.

3.3 Stage 3: User Preference Survey

While Stages 1 and 2 involved clinicians and therapists in identifying the design space and generating concepts, Stage 3 focused on BCSs, aiming to investigate their preferences about the features and interfaces of *CoBreath* , as well as potential barriers to integrating VR-based relaxation into their daily lives. We conducted an online survey with BCS (n = 41) to gather user preferences and requirements, which informed *CoBreath* design details. All respondents were female BCSs from urban hospitals. They ranged in age from 30 to 65 years, had completed primary treatment, and were currently undergoing outpatient rehabilitation. The survey consists of 15 questions, covering three domains: (1) Peer Support and Companion; (2) VR Scene for Mindfulness Practice; (3) Facilitators and Potential Barriers.

Results. As shown in Fig. 4, the user survey further confirmed the findings from the first two stages, identified more detailed BCS' preferences and requirements for system design. **Peer-support and companion.** Most BCSs preferred not to practice alone (85.37%), among those 41.46% preferred practicing with a peer BCS and 34.13% preferred with their spouse. This preference resonates with findings of Stage 2, emphasizing the need of peer support, while also distinguishing which companion types (peer survivors, family members) BCS themselves find most desirable during practice. **Calm and low-complexity VR scene for mindfulness practice.** Participants converged on calm, low-complexity environments, specifically cozy indoor and restorative forest scenes, which were equally preferred (both 34.15%). Color choices leaned toward blue(36.59%) and green(31.71%), with a secondary affinity for pink(24.39%). These findings suggested simple scenes, a stable camera perspective, and abstract visuals in VR design that guide breathing without requiring complex user interaction.

Facilitators and potential barriers. As shown in Fig. 4-c, visualization of therapy effects (56.10%), and the aesthetics of visual (34.15%) were identified as key facilitators. These findings suggest that BCSs prefer receiving progress feedback during relaxation training and value feeling emotionally supported by a gentle, aesthetically pleasing environment. On the other hand, the absence of professional guidance (73.17%), limited attention or awareness within BCS care (39.02%), inadequate peer support (36.59%), and suboptimal home environments (29.27%) were identified as the primary obstacles. In summary, survivors' willingness to use a VR-BF system depends not only on the system itself, but also on whether it can provide clear cues of therapeutic benefit, compensate for the lack of professional supervision, and fit into everyday routines that are often noisy, busy, and socially fragmented.

3.4 Design Goals and Features

As shown in Fig. 3, the main findings from the user research studies were further synthesized into three main design goals, which were incorporated into the *CoBreath* system as its key innovative features.

3.4.1 *Shaping a calming environment for relaxation experiences.*

The first primary design goal was to create a virtual environment that is calming while also accommodating the biofeedback display. The visual design in VR was intentionally abstract, ambient, and spacious, with uncluttered scenes and soft gradients. This design minimized visual distractions in the VR environment, guiding users to concentrate on their breathing and interoceptive sensations. Specifically, we designed a minimal embodied representation of users, situated within a Zen-inspired meditation environment as

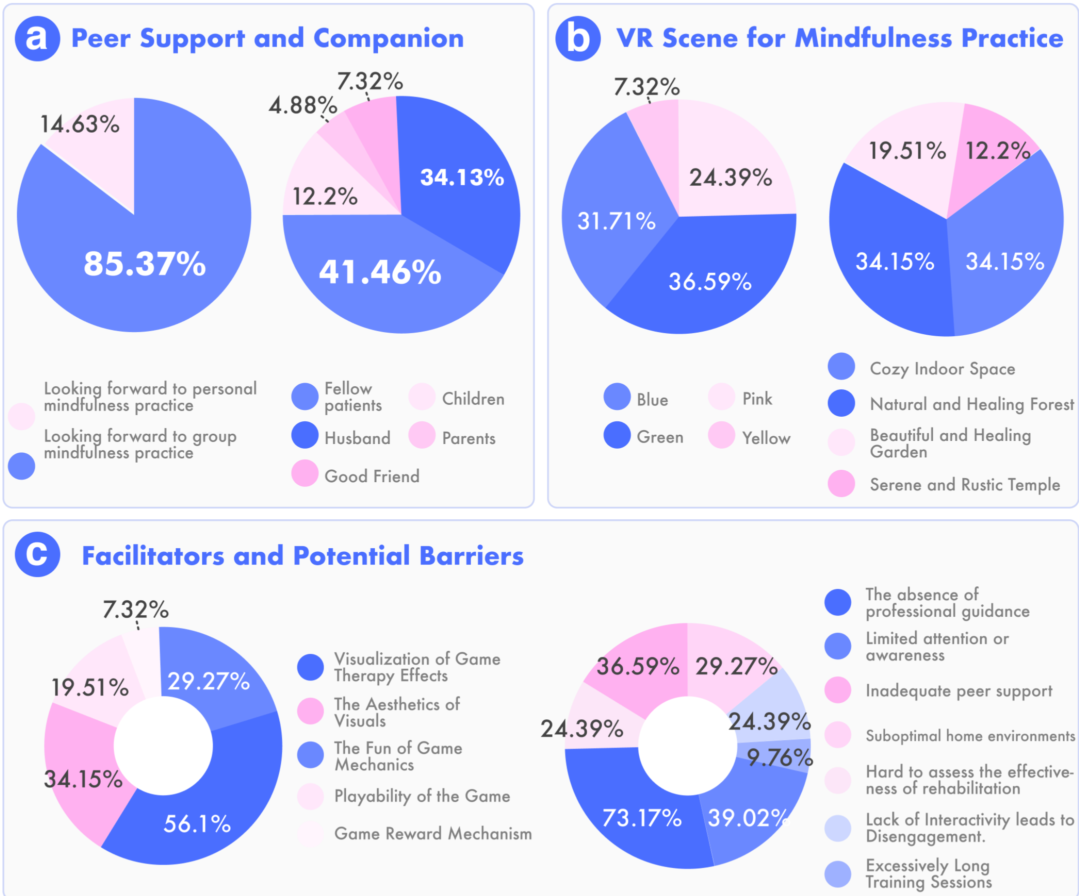

Figure 4: The results of the user survey with 41 BCSs on their preferences regarding VR-BF system design.

shown in Fig. 1. Regarding the biofeedback display, our goal was to leverage ambient light changes to design a minimally demanding interface that stays unobtrusive yet renders respiration-linked feedback. Using changes in virtual light elements, such as halo-like glows and subtle light movement, allows the biofeedback display to blend naturally into the VR environment while remaining intuitive and easily perceivable

3.4.2 ***Dyadic Biofeedback for peer-supported breathing exercise***. The *CoBreath* was designed to integrate two key physiological signals: *respiratory rate* and *HRV* into a dual-modality biofeedback system. We aimed to incorporate a dyadic cooperative interaction model to enhance user engagement and emotional connection during relaxation training. Specifically, we adopted a symmetric awareness design, wherein both users can view abstracted, non-numeric, color-coded representations of each other's breathing and HRV within a shared virtual space. This mutual visibility could support synchronized breathing rhythms and foster intentional social presence. Given that BCSs often engage in rehabilitation either in hospital or at home, the system could be situated within co-located collaborative settings. We also designed cooperative co-breathing tasks and a rewarding mechanism to ensure a low-pressure, non-confrontational environment that promotes social bonding and shared recovery.

3.4.3 ***Intuitive Interfaces of Biofeedback mapping***. Our findings emphasise the significance of carefully designing the mapping between biofeedback data and VR-based displays. This is particularly crucial for multimodal biofeedback, such as including HRV and breathing data. An overly complex biofeedback display can increase cognitive load and even anxiety. Thereby, our goal was to use natural mapping, where visual changes are easily and intuitively understood and associated with the physiological data. This concept incorporates the use of visual effects of light elements. On the one hand, these elements offer a rich set of parameters (size, location, color, transparency) that can be coupled with breathing and HRV. On the other hand, the *breathing light* that expands and contracts or brightens and dims with inhalation and exhalation is common in meditation apps and ambient devices. This intuitive visual metaphor helps users easily understand and follow breathing patterns, providing immediate, real-time guidance without requiring verbal instructions. By adhering to these principles, VR biofeedback interfaces strive to support intuitive awareness of physiological states, facilitate effective self-regulation, and optimize the user experience while minimizing unnecessary cognitive effort.

4 System design and implementation

4.1 System Overview

In this study, we developed *CoBreath*, a dyadic VR biofeedback (VR-BF) system that enables BCSs to practice paced breathing for relaxation training. Different from traditional biofeedback systems that support individual users in self-regulation, *CoBreath* enables a shared relaxation experience and non-competitive breathing practice with a peer or family member. As shown in Fig. 5, *CoBreath* system comprises three components: (i) Wearable biosensors, including a fabric breathing belt to unobtrusively capture respiration and a wrist-worn photoplethysmography (PPG) sensor to measure HRV; (ii) A biofeedback program that processes breathing and HRV data to drive biofeedback displays, guiding users through breathing exercises and relaxation; (iii) a VR relaxation environment that supports two users performing breathing exercises simultaneously. We will elaborate on each part in the following sections.

4.2 Wearable Bio-sensors

In this study, we developed a wearable breathing sensing device that comprises two parallel resistive elastic fabric sensors (Length 100 mm × height 10 mm × thickness 1 mm), an ESP32-C6 microcontroller board, and a 3.7 V rechargeable lithium battery. The fabric sensor belt could unobtrusively and comfortably measure the user's breathing signal and transmit it to the biofeedback program via Bluetooth in real-time. In addition, we developed a wrist-worn HRV sensing device comprising a PPG sensor, an ESP32-C3 microcontroller, and a 3.7 V rechargeable lithium battery. All these electrical components are integrated into a 3D-printed watch-style enclosure with a nylon wristband. The raw pulse signal is captured by the PPG sensor and preprocessed on the microcontroller to detect heartbeats and calculate inter-beat interval (IBI) data in milliseconds. The IBI data is then transmitted via Bluetooth to the biofeedback program for further processing.

4.3 VR Design for *CoBreath*

Building on our formative findings that BCSs preferred calm, cozy, and low-complexity scenes and were easily distracted by overly detailed decorations, we abstracted these preferences into the core concept of a *luminous environment*, where light rather than concrete objects becomes the primary design element. As a core abstract medium, *light* supports emotion regulation and attentional focus [99], carries broadly shared symbolic meanings across cultures [30], and affords rich variation and interaction. We constructed a spacious VR scene with a sense of privacy while still supporting a shared activity. The ambient light in the VR environment was used as an important emotional stimulus that gives participants a pleasant, relaxed impression [5]. The scene follows an abstract style, using non-representational shapes, color, and texture to construct a broad circular space. A large dome at the top houses the primary light source, enhancing depth and atmosphere. The overall space is vast and open, drawing attention back to one's own body and to the neurofeedback cues. To accommodate time of day and training preferences, we provide two ambient palettes: a low-saturation warm-pink scheme for daytime to convey warmth and safety, and a low-saturation blue-gray scheme for nighttime to convey calm and steadiness. These palettes allow *CoBreath* to deliver distinct affective experiences across modes, helping patients achieve optimal immersion and comfort during training.

To avoid visual burden, we designed the patient avatar with minimal complexity: a rounded head and torso built from basic geometries, simplified triangular limbs, and facial features. The avatar is simple yet friendly, seated on the floor, so that users feel comfort and companionship during rehabilitation. We employ *light effects (e.g., light fields and halo rings)* as the primary design medium for biofeedback, such as rising and falling *light fields*, moving *halo rings*, and dynamic particle bursts. For interaction design, upon entering the VR space, each user completes a 1-minute preparation phase to adjust breathing and optionally set environmental parameters (e.g., color and brightness). To further support immersion and relaxation, the system plays a continuous background track of slow-tempo, airy instrumental music, designed to be calming and unobtrusive. During relaxation sessions, the avatar of the user sits in the center of the space. In dyadic mode, they sit face-to-face in each center of two *light fields*.

4.4 Slow-paced Breathing for Relaxation Training

In this work, *CoBreath* is designed to facilitate paced breathing exercises, namely *4-8 slow-paced breathing* (inhale 4s, no hold, exhale 8s) as the core cadence within a relaxation session. As a simple, easily taught technique, slow-paced breathing [42] is widely used in relaxation training and stress management due to its evidence-based physiological benefits for stress reduction [70]. Paced breathing exercises [127] could encourage individuals to become aware of their breathing patterns and intentionally adjust rate and depth, have been shown to enhance parasympathetic activity, thereby improving autonomic balance and promoting relaxation. We selected 4-8 slow-paced breathing because it presents a moderate challenge that most BCSs can learn quickly. A soft voice–guided 4–8 breathing cue was integrated into the biofeedback program to help users regulate their breathing patterns to the target rhythm. With this guidance (e.g., "inhale slowly for four seconds," "now exhale for eight seconds"), users do not need to count the timing themselves and can instead focus fully on their breathing during the relaxation session. In addition, the 4–8 breathing cue was used to assess users' slow-paced breathing performance and to calculate the corresponding feedback.

4.5 Biofeedback design

In the *CoBreath* system, we integrated two biofeedback modalities: *Respiratory Biofeedback* and *HRV Biofeedback* to support slow-paced 4-8 breathing exercises. Based on prior studies [120, 121], we designed a natural mapping between VR interfaces and biofeedback data, making sure the biofeedback is intuitive to understand. The location, size, and color of *visual light elements*, including *halo rings* and *light fields*, are mapped to users' respiration and HRV data for real-time biofeedback display. The details of this mapping are elaborated below.

4.5.1 ***Respiration Biofeedback.*** As shown in Fig. 6, in the **individual mode**, users are immersed in a VR *light field* and surrounded by a *halo ring*. The *light field* visualizes users' real-time respiration

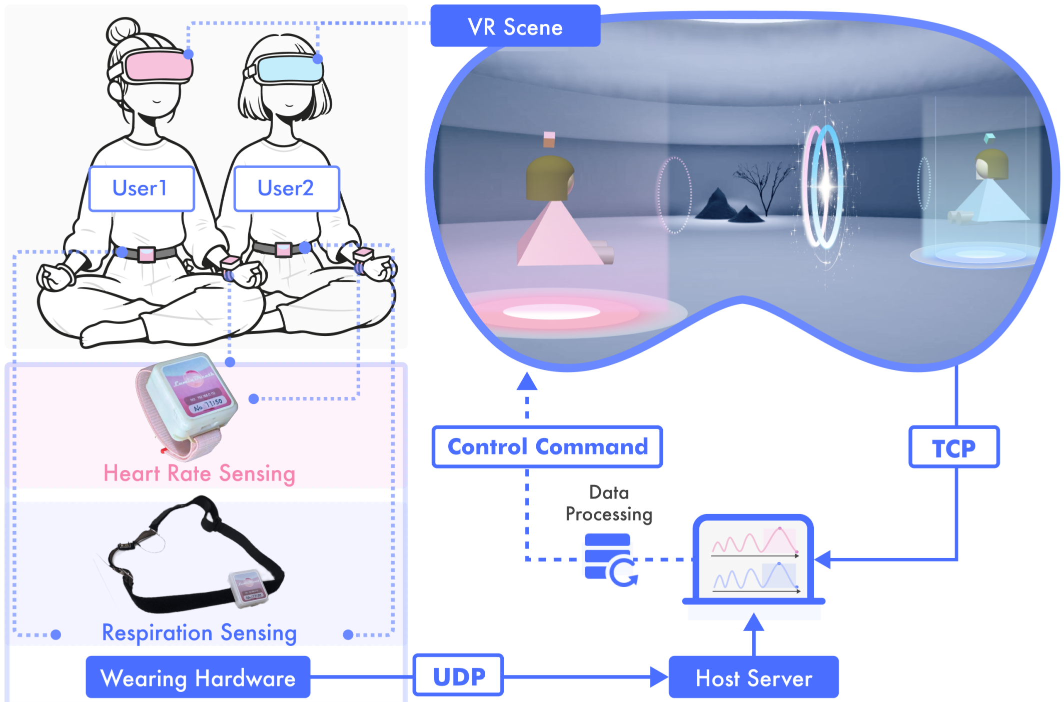

Figure 5: The system overview of *CoBreath* dyadic VR biofeedback system. Each user wears a respiration belt and a heart-rate sensor; the raw physiological signals are streamed via UDP from the wearable hardware to a host server, where they are filtered and processed in real time to extract breathing phase and HRV-related features. The host server then sends high-level control commands over a TCP connection to the VR application, which updates the light field, halo rings, and other visual elements in the individual and dyadic VR scenes accordingly.

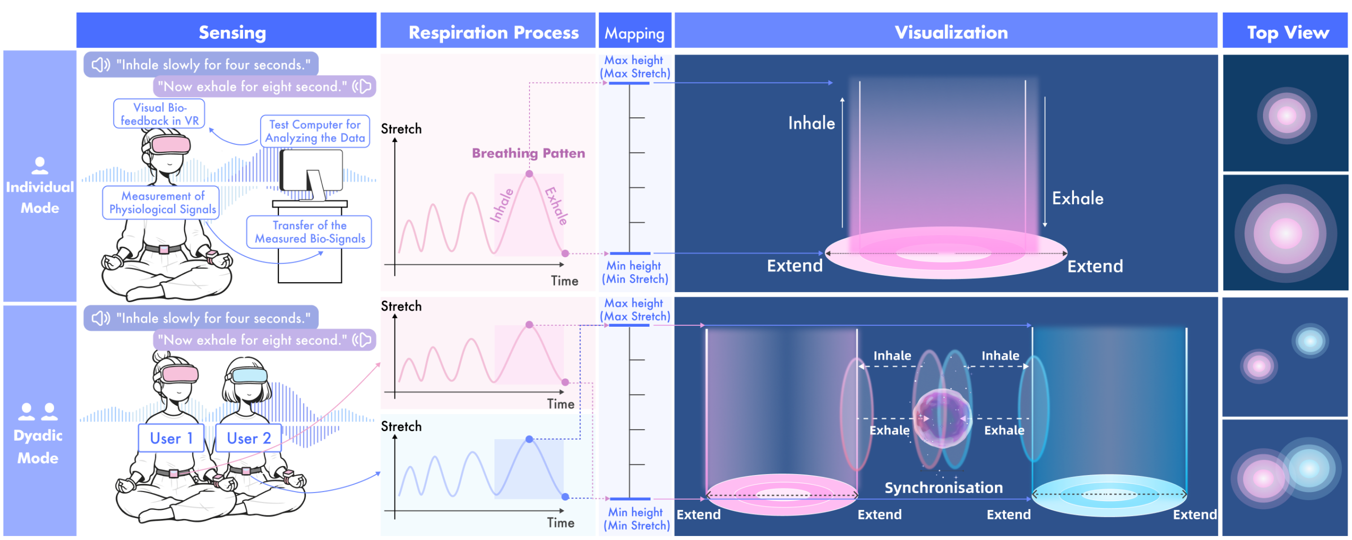

Figure 6: *CoBreath* biofeedback information display for individual (top) and dyadic (bottom) modes. The user's breathing signal is represented by *light field* height in individual mode and movements of *halo rings* in dyadic mode. HRV (RMSSD) is represented by color of light.

through changes in its height: it rises during inhalation and falls during exhalation, making the breathing pattern easily perceivable and understandable. The ground *halo ring* visualizes the user's performance in 4–8 paced breathing. When users achieve and maintain the targeted 4–8 breathing pattern, *halo ring* gradually expands outward to indicate positive outcomes. If the target pattern is not maintained within the given time frame of 1 minute, the *halo ring* will slowly return to its baseline state (near the body of the embodied avatar). In the **dyadic mode**, we prioritize psychological comfort and mutual support. Within the shared virtual environment, each participant sits inside their own *light field* that rises and falls with their breath. In addition, each user faces a vertical *halo ring* that can move forward and backward. The *halo ring* changes size and distance based on the user's breathing, expanding and moving outward during exhalation, and contracting toward the user during inhalation. When both users achieve synchronous breathing aligned with the targeted slow-paced pattern, their *halo rings* merge together and trigger a particle diffusion effect as a reward. This synchronized visual metaphor is designed to foster a sense of co-achievement, enriching social interaction and emotional bonding between two BCSs.

4.5.2 ***Heart Rate Variability Biofeedback.*** In this study, we used RMSSD (Root Mean Square of Successive Differences) as the HRV index for biofeedback, as it is widely regarded as a reliable indicator of autonomic balance and physiological relaxation [79]. In the *CoBreath* system, the user's real-time RMSSD is calculated from each inter-beat interval data and mapped to the color of *light fields* and *halo rings*. The PPG module provides an updated RMSSD estimate every 1.28s. For the time-window length of color feedback, we apply a moving average over the most recent 50 RMSSD samples ($\approx 64s$) to reduce short-term jitter and reflect the user's recent overall relaxation level. Guided by common ranges reported in prior work [92], we developed the HRV biofeedback mapping as follows: When RMSSD > 40 ms, indicating a relatively relaxed state, the *light field* appears soft blue. For RMSSD between 15–40 ms, signaling a moderate state, the *light field* shifts to green hues. When RMSSD < 15 ms, associated with suboptimal relaxation, the *light field* displays pink tones. These real-time color changes are integrated with the system's existing respiratory feedback mechanism, such as the rising/falling *light fields* and animated *halo rings*, creating a multimodal biofeedback display. The HRV biofeedback display is the same in both individual and dyadic modes.

5 Study One: System feasibility from the clinical perspective

Before conducting the patient-facing study, we used a mixed-methods protocol to evaluate the feasibility of *CoBreath* with the clinicians in a real clinical setting. The user study was conducted between November 21, 2024, and November 23, 2024, as part of a formal research collaboration with the hospital. Ethical approval was obtained from the institutional review board of Tianjin Medical University Cancer Institute and Hospital (approval number: bc20241747). All procedures followed the hospital's guidelines and regulations. All participants received a written information sheet and provided written informed consent for participation and for the use of anonymized quotes in publications.

5.1 Participants

As shown in Fig. 8, we recruited ten clinical experts from the rehabilitation department of a tertiary hospital, including three physicians and seven rehabilitation therapists, with an average age of 29.2 (SD = 10.32). All of them are newly recruited and did not participate in the previous formative study. Their hospital-based clinical experience ranges from 3 to 39 years. All participants were familiar with postoperative breast cancer rehabilitation pathways and the management of common symptom clusters (e.g., insomnia, fatigue, pain). None of the participants had ocular conditions or a history of severe motion sickness or vertigo.

5.2 Procedure

Fig. 7 (a) shows the procedures of the study, which include four steps: (1) Introduction (3-min): we first briefed each participant on the aim of the study and the training content. We introduced *CoBreath* 's hardware, including the Pico 4 VR headset, the wearable breathing belt, and the wrist-worn HRV sensor. We then demonstrated how to use *CoBreath* for relaxation training. (2) Experience system (12-min): participants then experienced both *individual mode* and *dyadic mode*. Each trial lasted five minutes. And they had a two-minute rest in between. (3) Questionnaires (5-min): Afterwards, they completed two standardized questionnaires: the System Usability Scale (SUS), the Credibility and Expectancy Questionnaire (CEQ). (4) Semi-structured interview (20-min): At last, participants took part in a semi-structured interview.

5.3 Measurements

5.3.1 Credibility and System Usability. Based on previous work [46, 108], we use *Credibility/Expectancy Questionnaire (CEQ)* [23] to evaluate whether clinicians regard *CoBreath* as a plausible, logical, and potentially helpful relaxation training tool in breast cancer care. The CEQ measures two main aspects: *Credibility* and *Expectancy*. In addition, we used the *System Usability Scale (SUS)* to assess the system's usability and acceptance. Each participant rated 10 items on a 1–5 Likert scale covering perceived *usability*, *ease of learning*, and *satisfaction*.

5.3.2 Semi-structured interview. At the end of the study, a semi-structured interview was conducted in the hospital's clinical consultancy room, with each clinician participating in person. All interviews were conducted in Chinese, audio-recorded with participants' consent. Each interview lasted 20 min on average. The interview guide was developed based on previous interview studies on distress and symptom management [52, 75]. The guide covered (i) *overall impressions (immersion, burden)*, (ii) *device fit/comfort and signal stability*, (iii) *suitability of the 10-minute two-to-one breathing task and dyadic mode*, (iv) *clarity/motivation of light-based biofeedback*, and (v) *clinical deployment considerations*. The interview transcripts were analyzed using an inductive thematic analysis [11]. Two authors independently coded the transcripts, then met to reconcile codes and consolidate them into a shared codebook. Related codes were iteratively grouped into higher-level categories, which were refined through several rounds of discussion into overarching themes.

5.4 Results

5.4.1 Quantitative results. Fig. 9(a) shows the results of CEQ. The avarage score of *Credibility* (Q1–Q3) is 22.8 and *Expectancy* (Q4–Q6)

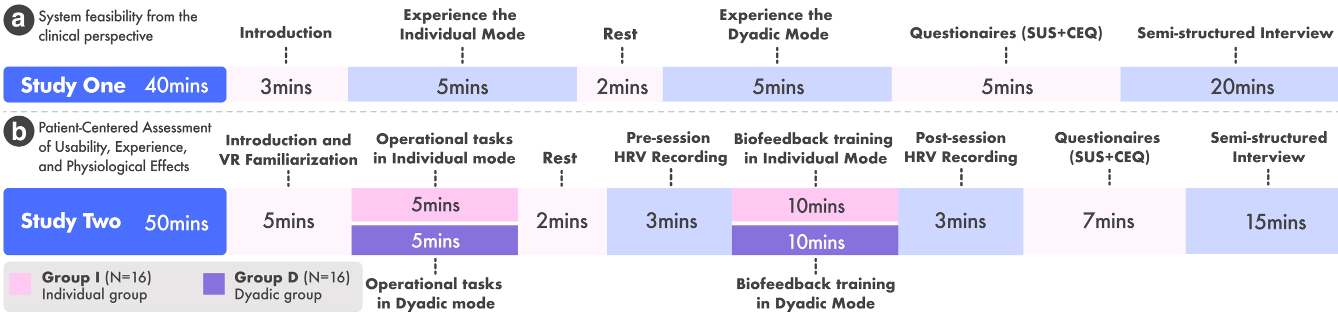

Figure 7: Procedure of Study one and Study two.

Figure 8: In Study 1, the participating clinicians evaluated *CoBreath* in two working modes: (a) Individual mode and (b) Dyadic mode.

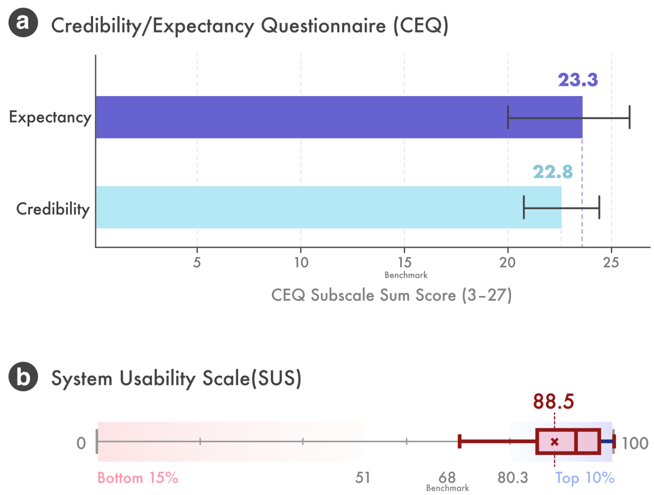

Figure 9: Study one results (a) Credibility/Expectancy Questionnaire (CEQ) (b) System Usability Scale(SUS).

averaged at 23.3. According to the one-sample t-test, both are significantly higher than the mid-point reference of 15($p < .001$). These results indicate that clinicians perceived the *CoBreath* as a credible system for BCSs care. They also expected it to be effective in facilitating paced breathing exercises in relaxation training. Moreover, clinicians rated *CoBreath* as highly usable (M = 88.5, SD = 10.35), significantly above the benchmark score of 68 ($p < .05$). These results place *CoBreath* in the "excellent" usability range on the SUS interpretation scale, as shown in Fig. 9 (b).

5.4.2 Qualitative results. ***1) Immersion and relief from hospital stress.*** Clinicians consistently described the experience as *highly immersive and calming*, helping users detach from tense, noisy wards and settle into practice. For instance, PT7 noted, *"I felt the immersion was particularly strong. I could fully engage in the environment and practice mindfulness breathing training."* Most clinicians viewed *CoBreath* as an effective way to help patients temporarily *"step out"* of stressful clinical settings and reduce context-induced mental load to support attention. In addition, clinicians also stated that the abstract visual display of physiological data felt intuitive and soothing, making it easier to shift attention to interoception and breathing rhythm. As PH3 commented, *"wearing the headset, I felt detached from the tense and noisy hospital environment, and training in the system felt particularly calming."*

2) Expected clinical benefits and the role of dyadic practice. Clinicians also anticipated potential benefits of dyadic mode and peer-supported practice for *focus, motivation*. For instance, PH2 stated *"I believe that consistent use of this (dyadic) system could greatly improve somatic symptoms. I am very confident recommending it to patients with these symptoms."* Several clinicians believed that the dyadic mode could better support BCSs in staying engaged and focused. As PT2 noted, *"in the dyadic mode, I could focus more on mindful breathing, whereas in individual mode, I tended to feel sleepy."* We interpret "sleepiness in solo" as arousal dropping too low (overly soothing), while dyadic practice introduces mild social arousal and visible pacing constraints that stabilize attention.

3) Recommended practice environments and safety. To protect mindfulness and comfort, clinicians advised quiet, ventilated, non-crowded rooms with back support. As PT10 suggested, *"this system works best in a quiet room with a sofa. In the therapy room, other rehabilitation devices produce beeping sounds that can disrupt relaxation experience"* They also recommended structured guidance before use and prompt clinician intervention if discomfort arises, especially for patients with drainage bottles. In real clinical settings, explicitly defining "minimal-interference" conditions and safety thresholds both protects the mindfulness process and satisfies medical safety. We therefore developed a short pre-session checklist (headset strap fit, lens cleanliness, ambient noise control) and an onboarding procedure, which was used in Study Two with BCSs.

4) Enrich the modality of feedback and interactions. Therapists recommended enriching the sensory experience of the VR system and the interactions of the dyadic mode. For instance, PT5 noted *"it would be good to include some user-selectable environmental audio in the system to facilitate relaxation"*. Similarly, PT10 said *"it's best if patients can choose the environmental sounds in VR; I think natural sounds work best."* They mentioned that the relaxation training sessions could be optimized by transforming the VR environment into more natural settings: *"such as forests, lakes, or seaside scenes, to help patients enter a relaxed state more easily."* (PT1) Therapists also commented on the introductory guidance at the beginning of the VR session. In the current prototype, users are greeted by a brief voice-based guide that welcomes them into the environment and explains that they will practice slow breathing together with a partner avatar, accompanied by a short line of on-screen text. PT4 suggested that this "first prompt" could be more specific and contextual to help patients orient themselves in the dyadic space, for example: *"look around, your rehabilitation partner is in front of you."* In addition, some clinicians suggested adding subtle animated motion to avatars in dyadic mode, for instance, *"VR avatars could move and interact together"*.

6 Study Two: Patient-Centered Assessment of Usability, Experience, and Physiological Effects

This study was conducted between December 28, 2024, and February 13, 2025, at the rehabilitation department of Tianjin Medical University Cancer Institute and Hospital. Ethical approval was obtained from the institutional review board of Tianjin Medical University Cancer Institute and Hospital (approval number: bc20241747). All procedures followed the hospital's guidelines and relevant regulations. All participants received a written information sheet describing the study aims, procedures, and potential risks, and were informed that participation was voluntary and could be paused or withdrawn at any time. Given that all participants were breast cancer survivors in active rehabilitation, a rehabilitation therapist was present on site to monitor comfort and provide support, and all participants provided written informed consent for participation and for the anonymized use of their questionnaire and interview data in publications.

6.1 Participants

We recruited 32 female breast cancer survivors from Tianjin Medical University Cancer Institute and Hospital. Participants were aged between 32 and 67 years, with an average age of 51.4 (SD = 8.24). The inclusion criteria were a surgical history of unilateral total mastectomy, modified radical mastectomy, or breast-conserving surgery with axillary lymph node dissection or sentinel lymph node biopsy, and screening positive for somatic symptoms using the Somatic Symptom Scale–China (SSS-CN, 20 items; score range 20–80)[51]. All participants scored >30 (M = 43.4, SD = 9.12), indicating at least mild somatic symptomatology[33]. Besides, the participants with severe psychiatric or cognitive disorders, comorbid malignancies, or major organic diseases were excluded. Furthermore, none of the participants received any medical HRV or respiration biofeedback training.

As shown in Fig. 10, Participants were initially randomly assigned to either the Individual group (Group I) or the Dyadic group (Group D). Each group consists of 16 participants. We measured the average age and somatic symptom severity (SSS-CN score) of each group and then adjusted the participants to ensure these factors were balanced and comparable between the two groups. Specifically, the mean age was 50.4 years (SD = 6.3) for Group I and 52.4 years (SD = 10.4) for Group D. Baseline SSS-CN scores were 41.8 (SD = 7.1) for Group I and 43.9 (SD = 9.9) for Group D. Independent-samples t tests showed no significant between-group differences in age ($t(30) = 0.68$, $p = .50$) and or SSS-CN scores ($t(30) = 0.70$, $p = .49$). In accordance with the hospital's guidelines and regulations, all participants received a participant information sheet and signed a written informed consent form before joining the study. In the following sections, participants are labeled with a group letter (I or D) plus patient number.

Figure 10: In Study 2, the participating BCSs evaluated *CoBreath* in a 10-minute paced breathing relaxation session: (a) using Individual biofeedback mode and (b) using Dyadic biofeedback mode.

6.2 Procedure

We conducted the study in a quiet therapy room within a breast cancer rehabilitation center. Before the study, therapists conducted a baseline assessment of the participants, covering sleep, pain, fatigue, anxiety, and somatisation. As shown in Fig. 7 (b), the protocol proceeded as follows: (1) Introduction and onboarding (5-min): the participants watched a 3-minute video to get familiar with the working of *CoBreath* . Participants donned a Pico 4 headset and held one controller in the unaffected hand. We demonstrated basic operations. (2) Operational tasks (5-min): after launching the Unity application, each participant completed a set of tasks to become familiar with the VR environment and interactions. (3) Pre-session HRV baseline(3-min): after a 2-minute rest period, we collected 3 minutes of HRV data from participants as the baseline (4) Relaxation session with *CoBreath* (10-min): participants perform a 10-minute relaxation training using *CoBreath* . In Group I, participants used the individual mode, while in Group D, participants used the dyadic mode. (5) Post-session HRV recording(3 mins): after the relaxation training, we collected participants' 3-min HRV again. (6) Questionnaire and interview (22-min): Finally, participants completed the SUS and UEQ questionnaires. We then conducted a semi-structured interview with each participant individually in the same therapy room. The interviews lasted approximately 15 minutes on average. The interview aimed to gather subjective experience data to help interpret the quantitative results and it covered five aspects: (i) perceived relaxation and emotional state during the session; (ii) breathing effort or dyspnea; (iii) ease of following the 4–8 paced-breathing rhythm; (iv) perceived synchrony and co-presence with the partner in the dyadic condition (Group D); and (v) feelings of social support and willingness to continue relaxation practice.

6.3 Measurement and Data analysis

Study Two includes three quantitative measures of system usability, user experience, and relaxation effectiveness of *CoBreath* . The SUS questionnaire is the same as that used in Study One. Based on prior studies[34, 55], we assessed perceived user experience with the *User Experience Questionnaire (UEQ)* [93]. The full UEQ comprises 26 semantic-differential items grouped into six dimensions—*Attractiveness*, *Perspicuity*, *Efficiency*, *Dependability*, *Stimulation*, and *Originality*. In addition, users' HRV (RMSSD) was measured to evaluate *CoBreath* 's effectiveness in enhancing physiological relaxation[79]. Due to individual physiological differences, we did not compare absolute RMSSD values. Instead, we calculated the relative change in RMSSD before and after the relaxation session and compared this change between the individual and dyadic groups. Each participant completed a 3-minute resting baseline before training and a 3-minute post-session recording. The relative change in RMSSD was calculated using the following formula. This evaluation method has been validated in prior HRV research examining autonomic responses to stressors and interventions [2, 28]. For the qualitative interview data, the transcripts were analyzed using an inductive thematic analysis approach[11]. The details of the method are the same as in Study 1, as described in Section 5.3.2.

$$\text{Relative change in RMSSD} = \frac{\text{RMSSD}_{\text{post}} - \text{RMSSD}_{\text{pre}}}{\text{RMSSD}_{\text{pre}}}.$$

6.4 Results

6.4.1 Dyadic mode demonstrated superior usability compared to the individual mode. As shown in Fig. 11, both individual and dyadic modes of *CoBreath* were rated as *'Excellent'* in SUS usability scale (Group I: M = 85.78, SD = 8.98; Group D: M = 92.34, SD = 5.28). The SUS scores of both modes are significantly higher than the benchmark score of 68 ($p < .05$). Comparing between the two groups, a two-sample t-test indicated that the averaged system usability rating in Dyadic mode is significantly higher than the Individual mode ($t(24.27) = 2.52$, $p = .019$). This result suggests that participants perceived the dyadic biofeedback mode as more usable for supporting slow-paced breathing practice in relaxation training.

6.4.2 Dyadic biofeedback results in a better user experience compared to the individual mode. Fig. 12 shows the results of the UEQ individual group and the dyadic group. Two-sample t-tests ($\alpha = .05$) suggest that the dyadic group reported significantly higher scores on *Attractiveness*, *Efficiency*, *Dependability*, *Stimulation*, and *Novelty*, and *Efficiency*. On the *Perspicuity* subscale, the dyadic group reported lower scores with greater variability compared to the individual group, suggesting that users may have found the co-practicing breathing and the dyadic interface slightly more complex to understand. Overall, the dyadic mode is a more positive user experience on several core dimensions, suggesting that integrating peer support into a co-relaxation training may enhance user experience.

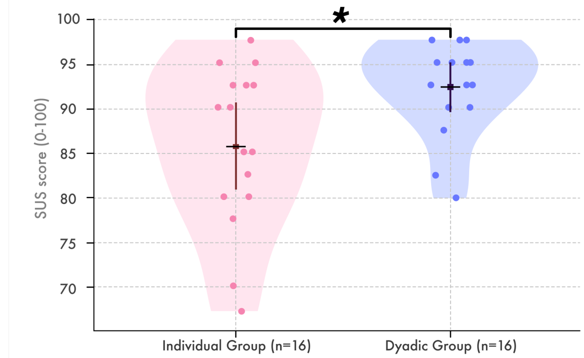

Figure 11: Results of System Usability Scale (SUS), * (p<0.05) significance.

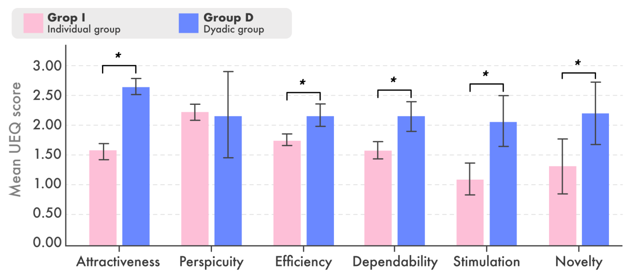

Figure 12: Results of User Experience Questionnaire (UEQ), * (p<0.05) significance.

6.4.3 Dyadic biofeedback facilitates physiological relaxation more effectively compared to the individual mode. As shown in Fig. 13, both individual and dyadic groups showed an increase in HRV (RMSSD) after a 10-minute relaxation session. In the individual group, the averaged RMSSD increased from 23.06 ms (SD=8.89 ms) to 25.44 ms (SD=9.34 ms)(Δ = +2.38 ms; ≈ +10.3%). In the dyadic group, the averaged RMSSD increased from 23.50 ms (SD=7.12 ms) to 28.00 ms (SD=9.16 ms) (Δ = +4.5 ms; ≈ +19.1%). Paired t-test shows the increase of RMSSD was significant for the dyadic group ($p < .005$). While the RMSSD increased 18.6% in the dyadic group, which is larger than 14.8% in the individual group, there is no statistically significant difference in the percentage increase of RMSSD between the two groups. These immediate HRV rises imply enhanced vagal activity and down-regulated arousal, consistent with our 4-8 paced-breathing rationale; the larger increase in dyadic group suggests the peer-supported co-breathing practice has potential to facilitate physiological relaxation.

6.4.4 Qualitative results. In this section, we present our findings from interviews with BCS participants following their relaxation sessions with *CoBreath* . Based on the qualitative results, three themes emerged from the inductive thematic analysis [11]: *VR immersive environment*, *Dyadic Biofeedback mode*, *Potential applications and areas for improvement.*

1) VR immersive environment fostered a strong sense of calm and relaxation. Most participants described *"noticeably calming down within minutes"* after using the *CoBreath* biofeedback system.

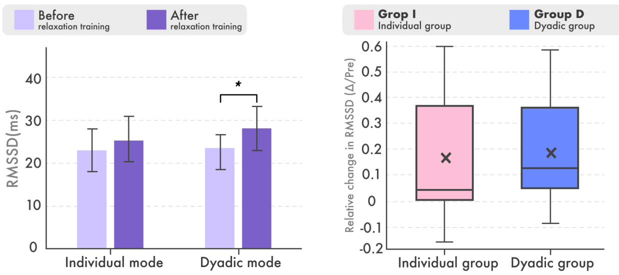

Figure 13: Results of HRV, (a) RMSSD before *vs.* after relaxation in two groups (* (p<0.05) significance), (b) the boxplot of the relative change in RMSSD before and after relaxation session in the Group I and Group D. The cross marks the mean and the horizontal line the median. Higher values indicate larger HRV increases after the relaxation session.

Many participants reported feeling significantly relaxed and emotionally calm. For instance, I1 described: *"Following the mindfulness guidance while watching the light changes in the scene and breathing deeply, I could clearly feel less fatigued, and the experience was relaxing."* D2 noted: *"When I breathed, the light around me changed accordingly, and I felt my mind becoming calm and peaceful."* Similarly, I7 noted: *"During this training, I felt my emotions calmed down somewhat."* Similarly, D10 noted that *"while practicing breathing exercise in the system, natural scenery like waterfalls would appear in my mind, I recalled the landscapes I had seen before, making me feel calm."* In addition, several participants associated these calming effects with sleep-related benefits. For example, D8 explained: *"watching the light rise and fall with my breathing, I almost fell asleep. It would be helpful to have a lightweight version to use before bed for people like me who have trouble sleeping."*

2) Dyadic mode helped sustain focused attention and made practice feel less solitary. *CoBreath* 's simple VR environment helped participants remain calm yet mentally focused. Several participants reported that they could better concentrate on paced breathing while using *CoBreath* . Some mentioned that although the VR space was simple and abstract, it helped to *"clear the mind,"* focus on bodily sensations, and stimulate imagination. For instance, I5 commented: *"I felt very relaxed with this spacious and open scene, and I enjoyed breathing with more awareness of it."*

Notably, participants in the dyadic group emphasized that the presence of a partner avatar enhanced both their focus and mood. For instance, D12 noted that *"breathing exercises with the avatar opposite me helped me focus and improved my mood,"* describing the practice as more engaging than doing breathing exercises alone. Dyadic group participants frequently mentioned that *"practicing together felt more encouraging"*, *"more interesting"*, and *"less lonely"*, even though they interacted only through avatars. Some participants also linked this sense of shared practice to emotional support: *"knowing that another person was breathing alongside them made the task feel more meaningful and easier to persist with."*(D2), which aligns with the importance of social connection and peer support highlighted in the formative study. We interpret this pattern as reflecting a gentle form of social arousal and shared rhythmic engagement: breathing in synchrony with a partner avatar fostered a sense of being accompanied and gently *"held accountable,"* which helped participants stay engaged with the exercise.

At the same time, the contrast between individual and dyadic experiences hinted at different relaxation profiles. Individual-mode participants more often described *"zoning out"* or *"almost falling asleep"* (I8), which they welcomed as helpful for sleep but which may be less conducive to actively learning the breathing technique. By comparison, dyadic group participants tended to characterize the practice as calm yet *"uplifting"* or *"motivating"*, suggesting that the social co-presence helped them stay pleasantly alert rather than drifting into drowsiness. No participant reported major discomfort or anxiety related to the dyadic setting. This result indicates that dyadic co-breathing may support relaxation partly by combining a soothing environment with a gentle sense of shared focus and accountability.

3)Potential applications and areas for improvement. Overall, participants appreciated the simple and user-friendly features of *CoBreath* , and suggested its potential for broader application. A few participants recommended extending peer-supported relaxation training to include familiar mentors or expanding beyond dyadic mode into group sessions with multiple users. For instance, D9 noted *"Yes, the system made me feel relaxed...it would be even better if my family and I practiced together."* D2 also expressed: *"Actually, I would be more willing and looking forward to participating in training with my family members."* and I5 suggested: *"If there are future improvements, I envision adding a group practice mode might feel even better."*. Moreover, participants also expressed support for promoting the system in hospital settings to benefit more individuals, as I4 suggested: *"I hope hospitals can introduce this system… I'd like to practice here regularly."* I3 also highlighted particular potential for those recently diagnosed: *"I was extremely anxious when first diagnosed. This system's breathing exercises could help patients at that stage."*.

Regarding the areas for improvement, some participants suggested that additional visual cues on the avatar (e.g., a moving light) or subtle sound cues could further enhance concentration. Besides, some suggested adding music or nature sounds to further support their focus. As I1 suggested: *"I've heard that singing bowl sounds are particularly therapeutic. It could be interesting to integrate specific frequency music elements, possibly combined with sensory feedback like aromatherapy, to further enhance focus and immersion."* I16 emphasized the importance of using accessible language, *"I think it's particularly good that the current guidance voice has no medical terminology. I can completely understand it, so I can focus on practicing."*

7 Discussion

In this study, we first identified the challenges that BCSs face in relaxation training, along with their preferences for VR-based biofeedback (RQ1). Then we developed a multi-model (respiration and HRV) VR biofeedback system and explored a dyadic biofeedback approach that integrated peer-support in paced breathing exercise for relaxation (RQ2). Through user studies with ten clinicians and therapists, we demonstrated that our design is user-friendly and meets clinicians' expectations (RQ3). Based on a hospital deployment and evaluation with 32 BCSs, we further demonstrated the effectiveness of *CoBreath* for relaxation training, as well as the significance of the dyadic mode in enhancing user experience (RQ4). In the following section, we revisit the quantitative findings from both studies and summarize key takeaways. We also discuss insights and design considerations derived from the qualitative findings, along with the study's limitations and directions for future work.

7.1 Key Takeaways

The CEQ and SUS results from **Study One** indicate that clinicians rated *CoBreath* as highly credible and effective for relaxation training, as well as intuitive and user-friendly in terms of system design. From a clinical perspective, these findings highlight *CoBreath* 's potential as a practical and adoptable tool for supporting relaxation training in BCS care. In **Study Two**, we focused not only on evaluating the effectiveness of *CoBreath* but also on comparing individual and dyadic biofeedback modes in terms of system usability and user experience. The SUS results suggest that while both modes were rated as 'excellent' in usability, the dyadic mode demonstrated superior usability to the individual mode. In addition, dyadic biofeedback produced a more positive user experience than individual mode, with significantly higher scores on *Attractiveness*, *Efficiency*, *Dependability*, *Stimulation*, and *Novelty*. The slightly lower Perspicuity scores suggest that co-practicing and navigating the dyadic interface may be more complex. Overall, these results indicate that integrating peer support into relaxation training can enhance engagement and satisfaction, though interface clarity should be considered. More importantly, while both individual and dyadic biofeedback increased HRV (RMSSD) after a 10-minute relaxation session, indicating effective physiological relaxation, the dyadic group showed a larger mean increase (+18.6% *vs.* +14.8%). These findings suggest the potential benefits of incorporating dyadic, peer-supported interactions in biofeedback-based relaxation training.

7.2 Design Implications

7.2.1 Designing dyadic biofeedback for collaborative interactions. Based on quantitative results, the dyadic mode yielded higher SUS and UEQ scores and a larger increase in RMSSD compared to the individual mode. The qualitative findings also highlight the potential of dyadic biofeedback that integrates peer support and social connection into slow-paced breathing exercises. Traditional biofeedback paradigms [119] have largely focused on single-user scenarios, where users rely on physiological feedback to learn self-regulation alone or with the assistance of a therapist. Such fixed, standard feedback can lead to decreased engagement over time[120]. While HCI technologies [91, 117] have been explored to address this challenge, the incorporation of social interactions or shared experiences remains underexplored. *CoBreath* introduces a dyadic biofeedback mode as a proof of concept, embedding paced-breathing biofeedback into a shared VR environment. Two users sit in the same virtual space, see each other's avatars, perform breathing exercises together toward a shared goal, and receive a joint visual "reward"(merging halo rings and particle diffusion) when both maintain the target breathing pattern. Qualitative findings suggest several ways in which dyadic biofeedback design may support relaxation practice. Participants in the dyadic condition frequently described *"breathing together"* with a partner avatar, feeling *"less alone"*, and *"more motivated"* to stay engaged in performing breathing exercises. For some, the presence of another cancer survivor partner made the practice feel more meaningful and supported. These accounts offer a plausible explanation for why the dyadic mode was experienced as particularly positive in terms of user experience, even though our HRV results only indicate a trend rather than a statistically robust superiority. At the same time, a few participants mentioned mild performance pressure or concern about *"keeping up"* with the shared rhythm, hinting that dyadic biofeedback can be a double-edged mechanism: it may both encourage effort and introduce anxiety if synchrony is experienced as evaluative. This underscores that dyadic biofeedback should be carefully crafted to foreground collaboration and psychological safety rather than competition. In *CoBreath* , we attempted to do so by using gentle, non-judgemental visualisations of co-regulation (shared light fields, merging halo rings) instead of explicit scores or rankings. Participants' suggestions to practise with family members or familiar peers, and to extend the system to small groups, further highlight that the perceived quality of social support may depend on who the partner is.

7.2.2 Enabling Personalization and Enriching Relaxation Modalities. Interviews suggest our abstract, ambient VR is not merely aesthetic; by lowering contextual load, it helped participants anchor attention on the breath and self-regulate, and the natural mapping from physiology to visuals was widely described as "immediately understandable." Yet, in unguided sessions, many users preferred nature imagery, and clinicians noted that nature-based scenes suit BCSs' evening wind-down routines. This choice aligns with evidence that exposure to natural environments calms affect and accelerates stress recovery [3]. Taken together, these insights argue for personalization across scene, embodiment, and modality rather than a single canonical design. Offering a selectable library that spans abstract and natural scenes (e.g., forest, lake, seaside) with adjustable ambience, and pairing scenes with breathing styles (e.g., Yoga breathing or extended-exhale pacing) so that scene and tempo jointly shape affect and arousal. Our choice of a static partner avatar minimized distraction but sometimes muted co-presence; some users even thought they were alone. Providing fine-grained control over avatar presence, stylization, and proximity—including privacy-preserving silhouettes or outlines—can balance relatedness with comfort in dyadic work. Clinicians also suggested that avatars with slight body movements and subtle facial expressions feel more approachable; to better support peer companionship during training, we envision customizable avatars (e.g., clothing and skin tone). Preferences also diverged by sensory channel: experienced practitioners reported deeper focus with eyes-closed practice, while some with sleep difficulty preferred music-assisted sessions. This motivates an auditory biofeedback track—music-therapy-informed mappings and gentle guided scripts—within the dyadic mode [14]. More broadly, several participants valued explicit relaxation guidance, which points to extensions beyond breath pacing, such as guided relaxation and progressive muscle relaxation (PMR) delivered via low-demand audio with optional visuals, progressively recommended as the system learns each user's preferred scenes, rhythms, and guidance level.

7.2.3 Expanding application scenarios. Though our system has been evaluated only within hospital settings, the rich feedback from participants reveals promising opportunities for broader scenarios. Firstly, participants' reports of drowsiness highlight that relaxation-induced drowsiness is a double-edged sword: beneficial for insomniacs but potentially causing distraction or excessive sleepiness during daytime training, suggesting a daytime/nighttime dual-mode approach. Indicating opportunities for developing sleep-focused applications where the system could be used before bedtime to clear daily stress and facilitate better sleep onset for individuals with insomnia, which is also a common somatic symptom. Secondly, while our study focused on peer support among patients, several participants expressed interest in practicing with family members, suggesting potential for home-based implementations that leverage existing family support structures. Thirdly, since breast cancer patients regularly undergo chemotherapy and radiotherapy treatments that involve waiting periods, the system's portability and immediate calming effects have the potential to provide valuable stress relief during these vulnerable moments through individual practice sessions. Finally, participants' enthusiasm for broader hospital implementation suggests opportunities for integrating VR biofeedback into dedicated therapy rooms or wellness spaces within medical facilities. These diverse application contexts highlight the system's potential for scaling beyond research settings to address real-world stress management needs.

7.3 Limitation and Future Work

In this work, through the design of *CoBreath*, we demonstrated the potential benefits of dyadic-mode biofeedback and provided insights into its design for relaxation training among BCSs. However, our study has limitations that point to directions for future research. First, regarding biofeedback design, we currently use a standard range of RMSSD for HRV biofeedback mapping (Subsection 4.5.2), based on normative data from healthy adults reported in prior studies. Although this standard approach is suitable for most participants, individual physiological differences mean that for some participants with inherently higher or lower HRV, the biofeedback display may be difficult to perceive. Therefore, we recommend including a personalization function during the initialization of the *CoBreath* system to determine each user's individual HRV range for mapping to the VR biofeedback display. Secondly, all BCS participants were recruited from a single urban tertiary hospital, and only basic demographic information (age and somatic symptom severity) was collected. Future studies should recruit more diverse survivor populations and gather more comprehensive demographic data to better understand the cultural and social factors influencing user needs.

Moreover, in Study 2, users' respiratory and RMSSD data during the 10-minute relaxation session were used solely for biofeedback and were not collected for analyzing breathing exercise performance. We used the relative changes in RMSSD before and after the relaxation session as the primary metric to assess the physiological outcomes of *CoBreath*. We recommend incorporating additional task-related metrics, such as breathing rate and pattern, as well as self-report measures (e.g., perceived dyspnea, subjective relaxation, or explicit synchrony scales), to more directly evaluate the effectiveness of *CoBreath* in facilitating slow-paced breathing and relaxation. Finally, our user study suggests short-term physiological and experiential benefits, but the durability and long-term clinical impact remain unknown. Future research should conduct longitudinal randomized controlled trials (8–12 weeks) comparing dyadic versus individual versus usual-care conditions, to better understand the effects and potential for clinical use. Third, our evaluation was conducted in a quiet therapy room rather than within routine rehabilitation workflows or patients' homes. Issues such as equipment setup, cleaning and maintenance, and scheduling within busy clinics may affect real-world uptake. Future research should conduct trials comparing dyadic versus individual versus usual-care conditions, deployments in outpatient rehabilitation and home settings, to better understand the effects and potential for practical environment use.

8 Conclusion

This paper introduced *CoBreath*, a dyadic VR biofeedback system to support paced breathing practice in relaxation training for BCSs. Through a formative study, we explored the context of stress management for BCSs, co-designed concepts with clinicians, and identified user needs and preferences of BCSs for VR biofeedback. Based on these findings, we derived three design goals to guide the development of *CoBreath*. The results from an expert study with clinicians and a field-deployed study with 32 BCSs show that *CoBreath* is usable, engaging, and credible. Importantly, the dyadic mode produced larger short-term HRV (RMSSD) gains than the individual mode and enhanced user experience and, suggesting that gentle co-presence can stabilize attention and deepen relaxation. Our findings contribute to the growing body of work on VR-based breathing practice and suggest broader potential in supporting the mental well-being of BCSs.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant 12411530123 and 62202335; Tongji University "Medicine + X" Interdisciplinary Research Project under Grant 2025-0648-YB-02.

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