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# Virtual reality experiences for breathing and relaxation training: The effects of real vs. placebo biofeedback

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ABSTRACT

Virtual reality biofeedback systems for relaxation training can be an effective tool for reducing stress and anxiety levels, but most of them offer a limited user experience associated to the execution of a single task and a biofeedback mechanism that reflects a single physiological measurement. Furthermore, user evaluations of such systems do not typically include a placebo condition, making it difficult to determine the actual contribution of biofeedback. This paper proposes a VR system for breathing and relaxation training that: (i) uses biofeedback mechanisms based on multiple physiological measurements, (ii) provides a richer user experience through a narrative that unfolds in phases where the user is the main character and controls different elements of the virtual environment through biofeedback. To evaluate the system and to assess the actual contribution of biofeedback, we compared two conditions involving 35 participants: a biofeedback condition that exploited real-time measurements of user's breathing, skin conductance, and heart rate; and a placebo control condition, in which changes in the virtual environment followed physiological values recorded from a session with another user. The results showed that the proposed virtual experience helped users relax in both conditions, but real biofeedback produced results that were superior to placebo biofeedback, in terms of both relaxation and sense of presence. These outcomes highlight the important role that biofeedback can play in virtual reality systems for relaxation training, as well as the need for researchers to consider placebo conditions in evaluating this kind of systems.

## 1. Introduction

Relaxation techniques have important implications for health and wellness. For example, they could improve personal well-being (Chandler et al., 2001) by lowering stress-related symptoms (Kim et al., 2013; Perciavalle et al., 2017), relieving anxiety (Chen et al., 2017; Hayama and Inoue, 2012; Kim and Kim, 2005a), reducing fatigue (Hayama and Inoue, 2012; Kim and Kim, 2005b), and controlling postoperative pain (Good et al., 2002, 1999). Furthermore, relaxation-based interventions for medical conditions can be beneficial as an adjunct to standard medical care (Mikolasek et al., 2018).

Slow and deep diaphragmatic breathing is a specific relaxation technique that has been shown to reduce stress, anxiety, and depressive symptoms (Brown and Gerbarg, 2005; Hayama and Inoue, 2012; Perciavalle et al., 2017). In addition to conventional instructor-led classes, breathing exercises can be learned through computer-based tools such as mobile breathing training apps (Chittaro and Sioni, 2014a). More recently, immersive virtual reality (VR) solutions for learning slow and deep diaphragmatic breathing have also been proposed (Blum et al., 2019; Michela et al., 2022; Rockstroh et al., 2021; van Rooij et al., 2016).

In general, the literature has shown that VR is a safe and effective medium for supporting stress and anxiety management, and for inducing relaxation in healthy individuals (Anderson et al., 2017; Kaminska et al., 2020; Riches et al., 2021; Soyka et al., 2016; Valtchanov et al., 2010) as well as patients (De Luca et al., 2019; Esposito et al., 2022). VR nature environments are often used for stress reduction and relaxation (Anderson et al., 2017; Valtchanov et al., 2010; White et al., 2018).

Some authors have recently considered the inclusion of biofeedback in VR systems for breathing and relaxation training. Biofeedback detects users' affective state by measuring their physiological activity and "feeds back" the detected information to users in real-time. In this way, it aims to enable users to learn over time how to change their physiological activity to enhance health and performance (Association for Applied Psychophysiology and Biofeedback, 2023), reduce stress-related symptoms (Bouchard et al., 2012), and increase users'

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feeling of well-being (Chandler et al., 2001). Existing biofeedback systems for relaxation provide users with biofeedback on breathing (Prabhu et al., 2020; Rockstroh et al., 2021; Venuturupalli et al., 2019), cardiac (Blum et al., 2019), electrodermal (Gromala et al., 2015; Shaw et al., 2011) or brain activity (Kosunen et al., 2016). They typically allow users to explore a virtual environment (VE) that represents nature settings, with a specific task to perform. Tasks often involve performing controlled breathing (Prabhu et al., 2020; Rockstroh et al., 2021; van Rooij et al., 2016), trying to relax (Blum et al., 2019; Chittaro and Sioni, 2014b; Shaw et al., 2011), following an audio guide (Gorini et al., 2010; Tinga et al., 2019; Venuturupalli et al., 2019), or practicing meditation (Kosunen et al., 2016).

The cost and complexity of adding biofeedback to a VR relaxation system must be adequately supported by evidence. In particular, the biofeedback system should provide more accurate feedback, and make relaxation easier to achieve, than the same system without biofeedback. However, the assessment of this aspect is rarely addressed in the evaluation of such VR systems. A placebo biofeedback condition should instead be added to the study when evaluating biofeedback systems. The placebo condition is a control condition in which unaware users are given a sham treatment instead of the real one to assess the actual effectiveness of the real treatment. It is commonly used in medical studies because factors such as user suggestibility can lead to measuring positive effects, and improvements in well-being, even with sham treatments. Therefore, the evaluation of VR-based biofeedback systems should carefully consider how traditional, non-VR biofeedback systems have been evaluated in medical studies, e.g., Goldenberg et al. (2019), Greenhalgh et al. (2010, 2009), Woodward et al. (2014), and follow those research methods to assess if their proposed biofeedback treatment is actually better than a sham treatment. However, to the best of our knowledge, among the available studies of VR-based biofeedback systems for relaxation training, only two considered sham biofeedback: the first is described in Chittaro and Sioni (2014b), but uses non-immersive VR and does not analyze relaxation effects, the second is described in Tinga et al. (2019) but the system provides a very primitive and limited VR experience (an empty VE that only displays a cloud moving towards and away from the user). Another area of VR application that includes breathing training exercises, but for a different purpose, is pulmonary rehabilitation. A review of studies on this specific application is presented in Pittara et al. (2023), and we examined them too in searching for possible studies that might include sham biofeedback.

The aim of this paper is twofold. First, we propose a novel, immersive VR-based biofeedback system that teaches users how to perform slow and deep diaphragmatic breathing by immersing them in a natural VE. Unlike existing systems that typically offer a limited experience focused on a single physiological measurement, our system uses biofeedback mechanisms based on multiple physiological measurements, and the VE changes based on user's breathing activity, skin conductance (SC), and heart rate (HR). The relationship between users' affective state and changes in the VE provides users with visual and auditory feedback of their breathing activity and relaxation. A voiceover guides the user along a narrative that unfolds in multiple phases. Instead of asking the user to simply perform a relaxation task, our system aims at engaging the user by making him/her the main character in a story that evolves through the performance of two main tasks required to advance in the narration. This richer and more varied user experience can promote prolonged use of the system, fostering the adoption of VR-based biofeedback systems for relaxation training.

Second, we carry out a placebo-controlled study involving 35 participants to investigate the relaxation effects of the system. To assess if the biofeedback mechanism is actually beneficial, we compare the results of a group of participants who used the system with real biofeedback and a placebo group that used the system with a sham biofeedback. In the biofeedback group, changes in the VE were controlled by the user's real-time physiological activity measured by sensors. In the placebo group, changes were instead controlled by a previous recording of physiological activity from a session with a random other user.

The paper is organized as follows. Section 2 analyzes the literature on VR-based biofeedback systems for relaxation training and the design of studies conducted on such systems. The design of our proposed system is described in Section 3. Then, Sections 4 and 5 describe in detail the user evaluation and its results, while Section 6 discusses the results. Finally, Section 7 presents conclusions and future work.

## 2. Related work

Slow and deep breathing is commonly used in anxiety and stress reduction approaches, e.g., Hopper et al. (2019), Perciavalle et al. (2017). Increased awareness of breathing leads to anxiety reduction, e.g., (Jerath et al., 2015), and relaxation improvement, e.g., Busch et al. (2012). Biofeedback can be employed to increase awareness of breathing activity, as well as other physiological parameters to alleviate stress (Yu et al., 2018). The Association for Applied Psychophysiology and Biofeedback defines biofeedback as a process that allows the user to learn how to change his/her physiological activity to improve his/her health and performance (Association for Applied Psychophysiology and Biofeedback, 2023). Biofeedback uses sensors to measure user's physiological parameters and then provides the collected information to the user in real-time in visual and/or audio form. Immediate feedback helps the user gain voluntary control over the physiological process and induces favorable changes. Over time, these changes can persist without continuously using instrumentation (Association for Applied Psychophysiology and Biofeedback, 2023).

### 2.1. VR-based biofeedback systems for relaxation training

VR-based biofeedback systems for relaxation training can use either non-immersive displays (such as PC monitors) or immersive displays (such as VR headsets). Table 1 summarizes the main features of such systems. As shown in the table, nine systems in the literature reproduce natural environments in land, maritime, or underwater settings (Blum et al., 2020; Gorini et al., 2010; Kosunen et al., 2016; Prabhu et al., 2020; Rockstroh et al., 2021, 2019; Sonne and Jensen, 2016; van Rooij et al., 2016; Venuturupalli et al., 2019). Three other systems respectively use the VE of an office, a maze, or a scary mansion to train relaxation during stressful situations (Chittaro and Sioni, 2014b; Schoneveld et al., 2016; Schuurmans et al., 2015). Two systems use an empty VE containing only a single 3D object whose movements respectively match users' SC or breathing (Shaw et al., 2011; Tinga et al., 2019).

Almost all VR-based biofeedback systems for relaxation training employ a single physiological sensor whose value is mapped into one or more VE elements. As shown in Table 1, seven systems use physiological measurements of breathing activity, four systems use HR or heart rate variability (HRV), while other four systems use SC, muscle, or brain activity. Only two systems use more than one physiological measurement: in Kosunen et al. (2016), alpha and theta brain waves are mapped into two different VE elements; in Chittaro and Sioni (2014b), data from facial muscle activity, SC and HR are used to derive a single stress value, that is mapped into the behavior of a character. It is worth noting that four systems that record users' breathing data do not rely on the traditional sensors used to that purpose in different settings, including clinical settings. They respectively use a hand controller placed on user's abdomen (Blum et al., 2020; Rockstroh et al., 2021), a handmade spirometer-like device (Sonne and Jensen, 2016), and a microphone (Venuturupalli et al., 2019).

To provide the user with feedback on his/her current physiological activity, existing VR-based biofeedback systems for relaxation training map user's physiological parameters into one or more of the following five categories:

**Table 1**
Categorization of VR-based biofeedback systems for relaxation training.

| Refs. | Display | VE | Physiological data used for biofeedback | Mapping of physiological activity | Type of mapping |
|---|---|---|---|---|---|
| (Chittaro and Sioni, 2014b) | Non-immersive (PC monitor) | Office setting | Cardiac activity, electrodermal activity, muscle activity of zygomaticus major and corrugator supercilii | Data from facial muscle activity, SC, and HR are used to derive a single stress value that is mapped into the behavior of a virtual character | Virtual character |
| (Schuurmans et al., 2015) | Non-immersive (PC monitor) | Three VEs: maze with a spirit, maze with a ball, table seen from above with two pairs of hands | Cardiac activity | Greater HR increases the color filling of a heart-shaped 2D icon; maintaining HR low allows to outrun the spirit from the maze; greater HR increases the ball size; greater HR increases opponent speed in a hand-slapping competition | Task difficulty;<br>2D data visualizations |
| (Schoneveld et al., 2016) | Non-immersive (PC monitor) | Scary mansion | Brain activity | Data from brain activity are used to derive a single relaxation value which is mapped on the gradation of light glowing from the avatar's helmet | Visual attributes of VE elements |
| (Sonne and Jensen, 2016) | Non-immersive (PC monitor) | Underwater setting | Breathing activity | Inhalations move the avatar upwards and exhalations move it downwards, resulting in forward locomotion | Locomotion |
| (Rockstroh et al., 2021) | Immersive (VR headset) | Two VEs:<br>hilly setting,<br>maritime setting | Breathing activity | Slow breathing moves the user forward in the VE; inhalations and exhalations change the color of elements in the VE, the grass growth, and the emission of particles from blossoms | Locomotion;<br>visual attributes of VE elements |
| (van Rooij et al., 2016) | Immersive (VR headset) | Underwater setting | Breathing activity | Slow and deep breathing moves the user forward in the VE; shallow breathing applies gravity which lies the user to the ground; inhalations and exhalations change the color and illumination of plants; inhalations and exhalations grow and shrink a 2D circle | Locomotion;<br>2D data visualizations;<br>visual attributes of VE elements |
| (Prabhu et al., 2020) | Immersive (VR headset) | Maritime setting | Breathing activity | Breath activity is shown with a line graph; maintaining optimal breathing rate makes fog disappear from the VE | 2D data visualizations;<br>visual attributes of VE elements |
| (Venuturupalli et al., 2019) | Immersive (VR headset) | Glade with a tree | Breathing activity | Inhalations and exhalations grow and shrink a 2D circle | 2D data visualizations |
| (Shaw et al., 2011) | Immersive (VR headset) | Empty (only a single 3D object) | Electrodermal activity | Lower SC moves the sun position until below the horizon, then it makes the moon rise | Visual attributes of VE elements |
| (Kosunen et al., 2016) | Immersive (VR headset) | Maritime setting | Brain activity | Greater theta wave lifts the user's floating position in the VE; greater alpha wave increases the opacity of an energy bubble surrounding the user | Visual attributes of VE elements |
| (Tinga et al., 2019) | Immersive (VR headset) | Empty (only a single 3D object) | Breathing activity | Inhalations and exhalations move a 3D cloud-shaped object closer and farther away from the user | Visual attributes of VE elements |
| (Rockstroh et al., 2019) | Immersive (VR headset) | Maritime setting | Cardiac activity | Greater HRV turns on lights, clears sky from clouds, moves a sailing boat, increases wind and wave sound volume, activates up to 7 lamps on a landing stage, lights campfire and flashlights with crackling sound | Visual and auditory attributes of VE elements |
| (Gorini et al., 2010) | Immersive (VR headset) | Three VEs: glade with a campfire, waterfall, maritime setting | Cardiac activity | Greater HR increases fire intensity, sea waves movement, waterfall movement, and size of pre-selected words or images related to personal stressful events | Visual attributes of VE elements |
| (Blum et al., 2020) | Immersive (VR headset) | Hilly setting | Breathing activity | Inhalations and exhalations change the color of flowers, rocks and tree fruits | Visual attributes of VE elements |

1. *Attributes of VE elements*: the system changes one or more attributes of elements within the VE following user's physiological activity. These elements are naturally embedded in the VE, e.g., clouds, plants, or fog. Ten systems map user's physiological activity into attributes of VE elements such as color, brightness, position, size, or quantity, e.g., amount of fog/clouds, or flames of a campfire. Incorporating feedback into the elements of the VE increases the salience and attractiveness of feedback, fostering motivation and focus (Blum et al., 2019; Rockstroh et al., 2019), and improving users' engagement.
2. *2D data visualizations*: the system employs two-dimensional data visualizations to display user's physiological activity. Unlike the previous category, these visualizations are overlaid on the VE. They can take different forms, such as icons, graphs, or circles that change in response to the user's physiological activity. Four systems use 2D visualizations: in Schuurmans et al. (2015), a heart-shaped 2D icon shows to the user his/her current HR by increasing the color filling of the icon as HR increases; in Prabhu et al. (2020), a line graph displays user's current breaths per minute (bpm) with a line, comparing it to another line that shows a breathing rate of 5.5 bpm; in van Rooij et al. (2016), Venuturupalli et al. (2019), the user can observe his/her breathing through a circle that grows with each inhalation and shrinks with each exhalation.
3. *Locomotion*: user's breathing activity controls a locomotion technique, allowing the user to navigate the VE. Three systems use breath-based locomotion. In Rockstroh et al. (2021), van Rooij et al. (2016), the user must maintain slow and deep breathing to smoothly and continuously navigate the VE. In a non-immersive platform game described in Sonne and Jensen (2016), the user controls the vertical position of a virtual fish through his/her inhalations and exhalations and must collect as many starfish as possible. The starfish are arranged following a sinusoidal path so the easiest and most comfortable way to collect them is by maintaining a slow and continuous deep breathing. It should be noted that when using immersive displays, a mapping on locomotion may increase the risk

of motion sickness because user's point of view moves continuously while his/her head remains still, causing a sensory conflict between the visual and vestibular systems (Reason and Brand, 1975).

4. *Task difficulty*: the system adapts the task difficulty to a physiological parameter of the user. Following the operant conditioning paradigm - i.e., the method of learning that encourages behavior change by using rewards and possibly punishments (Staddon and Cerutti, 2003) - the system trains the user to self-regulate his/her physiological activity in stressful situations. To succeed in the task, the user needs to maintain his/her physiological activity under a predefined threshold value. Exceeding the threshold indicates increased arousal of the user, who is penalized by increasing task difficulty. One system maps user's HR on task difficulty (Schuurmans et al., 2015). Since increasing task difficulty may elicit negative emotions and stress in users, this mapping allows users to train themselves to regulate such emotions in the presence of stressors (Lobel et al., 2016).
5. *Virtual character*: the system changes the behavior of a virtual character based on the physiological activity of the user. One system maps user's physiological parameters on a virtual character (Chittaro and Sioni, 2014b). User's data from facial muscle activity, SC, and HR are used to derive the user's stress level that is mapped into the affective state and behavior of the virtual character. Higher user's stress level leads to worse character's behavior, e.g., displaying anger and struggling in the completion of its tasks.

### 2.2. *Design and results of studies*

The studies of VR-based biofeedback systems for relaxation training can be categorized in non-comparative studies, within-subjects studies, or between-subjects studies, as shown in Table 2. Eight systems were evaluated with a longitudinal study using non-comparative (one study), within-subjects (two studies) or between-subjects design (five studies). The most frequent sample size was from 8 to 25 participants (seven studies). Larger sample sizes involved 35 to 45 (three studies), 60 to 72 (four studies), 86 to 138 (three studies) participants. One study involved 411 participants. Table 2 summarizes the structure and findings of previous studies about the effects of VR-based biofeedback systems for relaxation training.

Measures used in the studies can be categorized into self-reports by participants (subjective measures) and derived from user's physiological parameters (objective measures). As shown in Table 2, level of anxiety is the most used subjective measure, followed by relaxation, while the most used objective measures are HR and HRV, followed by breathing activity and SC.

In five studies, participants were asked to relax, while in ten studies they were asked to maintain slow or diaphragmatic breathing following the rhythm of a pacer or an audio guided meditation. In two studies, participants were asked to perform meditation exercises.

Regarding objective measures, five studies showed that cardiac (HRV or HR) parameters improved during or after the use of the system. However, no study found significantly different values of cardiac parameters between VR with biofeedback and VR without biofeedback conditions. Tinga et al. evaluated instead the VR placebo condition against the VR biofeedback condition finding a lower HR in the VR placebo condition than the VR biofeedback condition (Tinga et al., 2019). However, that system provides a primitive and limited VR experience that only displays a cloud in an empty VE. Regarding subjective measures, twelve studies found an improvement in anxiety, relaxation, stress, or pain scores after using the system. In three studies, no significant differences were found on subjective measures between biofeedback and non-biofeedback conditions, but two studies found differences between an immersive and a non-immersive VR biofeedback system (Blum et al., 2019; Rockstroh et al., 2019). The immersive VR biofeedback system used a rich biofeedback that mapped users' physiological activity on attributes of multiple VE elements, whereas the non-immersive VR biofeedback system used a simple biofeedback that mapped users' physiological activity on the color of a 2D circle. Results showed that the rich biofeedback led to less mind wandering and both greater relaxation self-efficacy and focus on the present moment than the simple biofeedback (Blum et al., 2019). Moreover, participants who tried the rich biofeedback perceived a faster passing of time, expressed greater intention to use the system, and were more likely to recommend it than participants who tried the simple biofeedback (Rockstroh et al., 2019). Finally, both studies found that the rich biofeedback resulted in a more enjoyable experience than the simple biofeedback.

Only two studies considered a VR placebo condition (Chittaro and Sioni, 2014b; Tinga et al., 2019). In Tinga et al. (2019), the system provides a very limited VR experience as previously described, whereas in Chittaro and Sioni (2014b), the system uses non-immersive VR and does not consider physiological measurements for statistical analysis. The scarcity and limitations of previous studies with a placebo condition prompt the need to investigate further whether the effects of a VR-based biofeedback system for relaxation training are actually due to the use of real biofeedback by comparing it with placebo biofeedback.

## 3. The proposed system

This section describes in detail the VR experience for breathing and relaxation training we propose and evaluate in this paper. We first describe the design goals of the proposed system, then we illustrate the VR experience, and we conclude by examining the employed biofeedback mechanisms.

### 3.1. *Design goals*

The proposed system was designed considering the following goals: (1) offering a VR experience set in a natural VE to enhance relaxation; (2) mapping multiple physiological parameters measured on the user to various elements of the VE during the VR experience; (3) providing breathing and relaxation training exercises, where the user is asked to achieve specific goals, fostering user's motivation and sustained engagement throughout the training process; (4) embedding the performance of training exercises within a story that could actively engage the user throughout the VR experience.

### 3.2. *Overview of the VR experience*

The VE was developed in Unity 2020.3.27f and experienced with a Meta Quest 2 headset. It visually represents a coastal natural environment with a long, narrow beach facing the sea, three islands of various sizes close to the shore, and a windmill standing on the largest island (Fig. 1a). Rocks, grass, trees, bushes, and crystals are arranged in the VE following the indication in Gao et al. (2019), that compared six natural VEs, each with a different percentage of greenery covering from 10 to 70% of the entire space, showing that the most effective natural environment for reducing negative mood had 10–30 % of the scene covered by vegetation. The user sits on a wooden bench with a bush at his/her right (Fig. 1b). We called the VE "Crystals Archipelago" after the many crystals scattered around it.

The experience begins around sunset with the VE initially covered in fog (Fig. 1c). To enhance the experience, a variety of environmental sounds are played. A calming background music soundtrack and the sounds of wind, waves, and gears that move the windmill blades are played during the whole experience. Moreover, environmental sounds are reproduced at specific times, such as when the crystals glow and when the user interacts with the bush.

The VR experience involves the user as the main character of a story narrated by a voiceover. Initially, the voiceover describes the Crystals Archipelago as a magical land that can connect with the user through magical crystals. The voiceover then explains that the user's life spirit is infused into nearby crystals and spread to all the other crystals in the Archipelago, bringing them all in synch with the user and making the

**Table 2**
Categorization of previous studies of VR-based biofeedback systems for relaxation training. Letters in the column “Task” refer to the conditions in the column “Experimental conditions”.

| Refs. | Design | Partic. | Experimental conditions | Measures | Task | Main statistically significant findings |
|---|---|---|---|---|---|---|
| (Chittaro and Sioni, 2014b) | Within-subjects | 35 | (A) VR biofeedback with a single-sensor stress detection algorithm<br>(B) VR biofeedback with a multi-sensor stress detection algorithm<br>(C) control condition (VR placebo biofeedback) | *Subjective measures*: perceived biofeedback quality, difficulty of relaxation training<br>*Objective measures*: none | Stay calm and relaxed to allow the virtual character to remain focused on progressing in its task | Perceived biofeedback quality higher in VR biofeedback with the single-sensor stress detection algorithm rather than the VR placebo biofeedback |
| (Schuurmans et al., 2015) | Longitudinal, non-comparative | 8 | VR biofeedback (8 sessions during four weeks) | *Subjective measures*: experience satisfaction, difficulty of training, behavioral problems in everyday life, anxiety<br>*Objective measures*: none | Stay relaxed to evade a spirit, exit from a maze without hitting the walls with a ball, and win a hand-slapping contest | No analysis of statistical significance |
| (Schoneveld et al., 2016) | Longitudinal, between-subjects | 136 | (A) VR biofeedback<br>(B) control condition (puzzle platform video game) | *Subjective measures*: experience satisfaction, anxiety<br>*Objective measures*: none | (A) stay relaxed to light up the game scene and advance in the game<br>(B) play the puzzle platform video game | No statistically significant results |
| (Sonne and Jensen, 2016) | Within-subjects | 16 | (A) control condition (casual conversation with the experimenter)<br>(B) VR biofeedback (first time)<br>(C) control condition (action maze chase video game)<br>(D) VR biofeedback (second time)<br>(E) control condition (casual conversation with the experimenter)<br>(F) traditional relaxation activity<br>(G) control condition (casual conversation with the experimenter) | *Subjective measures*: none<br>*Objective measures*: HRV (RMSSD) | (A) converse with the experimenter about the introduction of the study<br>(B) play the VR biofeedback game (i.e., maintain slow breathing to move the fish up and down following a sine wave, collecting as many stars as possible)<br>(C) play the action maze chase video game<br>(D) play the VR biofeedback game<br>(E) converse with the experimenter about the VR and game experiences<br>(F) relax as much as possible<br>(G) converse with the experimenter about all the previous tasks | RMSSD lower during action maze chase video game than all other conditions; RMSSD higher during second VR biofeedback game than first casual conversation with the experimenter |
| (Rockstroh et al., 2021) | Longitudinal, within-subjects | 45 | (A) control condition (no treatment)<br>(B) VR biofeedback (6 sessions during one week) | *Subjective measures*: experience satisfaction, usefulness of diaphragmatic breathing and relaxation, simulator sickness, ease of use, ease of performing diaphragmatic breathing, breath awareness, relaxation, stress, burnout, relaxation self-efficacy<br>*Objective measures*: breathing activity, share (i.e., percentage of the total training session duration) of inhalations and exhalations | (B) Maintain diaphragmatic breathing to move along a predefined path and advance in the game | Share of inhalations and share of exhalations for each VR biofeedback session higher than the average of all previous sessions (except for share of inhalations in Session 5); ease of performing diaphragmatic breathing higher in Sessions 3, 5, 6 than the average of all previous sessions; breath awareness and relaxation self-efficacy higher after VR biofeedback treatment than no treatment; stress and burnout lower after VR biofeedback treatment than no treatment |
| (van Rooij et al., 2016) | Non-comparative | 86 | VR biofeedback | *Subjective measures*: anxiety, positive and negative affect, performance pressure, experience satisfaction<br>*Objective measures*: breathing activity | Maintain diaphragmatic breathing to move, and explore freely the VE | Anxiety lower after VR biofeedback session than before VR biofeedback session |
| (Prabhu et al., 2020) | Longitudinal, between-subjects | 12 | (A) VR biofeedback<br>(B) control condition (no treatment) | *Subjective measures*: anxiety, pain, sense of presence, system usability<br>*Objective measures*: none | (A) Maintain slow breathing following a sine wave | No analysis of statistical significance |

(*continued on next page*)

**Table 2** (*continued*)

| Refs. | Design | Partic. | Experimental conditions | Measures | Task | Main statistically significant findings |
|---|---|---|---|---|---|---|
| (R.S. Venuturupalli et al., 2019) | Within-subjects | 20 | (A) VR biofeedback<br>(B) audio guided meditation | *Subjective measures*: global health, emotional distress/anxiety, emotional distress/anger, pain<br>*Objective measures*: none | (A) breathe following the rhythm of a pacer<br>(B) maintain awareness of breath while doing a meditation exercise (body scan) | Pain lower after session than before session in both conditions; distress/anxiety lower after session than before session in audio guided meditation |
| (Shaw et al., 2011) | Non-comparative | 411 | VR biofeedback | *Subjective measures*: relaxation<br>*Objective measures*: HR, SC, breathing activity | Stay relaxed | Relaxation higher after VR biofeedback session than before VR biofeedback session |
| (Kosunen et al., 2016) | Within-subjects | 43 | (A) VR biofeedback<br>(B) VR without biofeedback<br>(C) non-immersive VR without biofeedback | *Subjective measures*: meditation depth (i.e., negative feelings, relaxation, self-reflection, emotions arisen, sense of presence, feeling of non-duality)<br>*Objective measures*: none | Perform meditation exercises (body scan and focused attention); stress memory task after each meditation exercise | Negative feelings lower in VR conditions than non-immersive VR without biofeedback; relaxation, self-reflection, emotions evoked, and feeling of non-duality higher in VR conditions than non-immersive VR without biofeedback |
| (Tinga et al., 2019) | Between-subjects | 60 | (A) VR biofeedback<br>(B) control condition (VR placebo biofeedback)<br>(C) control condition (empty VE without 3D objects) | *Subjective measures*: tension, calmness, experience satisfaction<br>*Objective measures*: HR, HRV (RMSSD), alpha wave and theta wave (theta to alpha ratio) | Stress arithmetic task; breathe following an audio guided meditation | Tension and HR lower in breathing task than stress arithmetic task; calmness, theta to alpha ratio, and RMSSD higher in breathing task than stress arithmetic task; HR better in VR placebo biofeedback than VR biofeedback |
| (Rockstroh et al., 2019) | Between-subjects | 68 | (A) VR biofeedback<br>(B) 2D colored circle biofeedback<br>(C) control condition (video of a natural environment) | *Subjective measures*: mood (i.e., good-bad mood, alertness-tiredness, rest-unrest subscales), experience enjoyment, intention to use, recommendation, perception of passing of time, attentional focus<br>*Objective measures*: HR, HRV (RMSSD, SDNN, LF/HF ratio, coherence ratio) | (A) maintain deep diaphragmatic breathing following the rhythm of a pacer<br>(B) same as (A)<br>(C) stay relaxed while watching a video of a natural environment | Rest-unrest mood higher in VR biofeedback than video of a natural environment; HR lower during session than after session in all conditions;<br>RMSSD higher during session than before and after session in all conditions; SDNN, coherence ratio, LF/HR ratio higher in biofeedback conditions than video of a natural environment; experience enjoyment and attentional focus higher in VR biofeedback than other conditions; intention to use and recommendation higher in VR biofeedback than 2D colored circle biofeedback; perception of passing of time quicker in VR biofeedback than other conditions |
| (Gorini et al., 2010) | Longitudinal, between-subjects | 20 | (A) VR biofeedback (8 sessions over an unspecified period)<br>(B) control condition (no treatment)<br>(C) VR without biofeedback (8 sessions over an unspecified period) | *Subjective measures*: anxiety, worry<br>*Objective measures*: HR, SC | (A) Stay relaxed by observing the flickering campfire (Sessions 1,2), the waves lapping on a shore (Sessions 3,4), the waterfall (Sessions 5,6), stressful images (Sessions 7,8)<br>(C) same as (A) | Anxiety lower after treatment than before treatment in VR conditions; worry lower after treatment than before treatment in VR without biofeedback and no treatment conditions |
| (Blum et al., 2019) | Between-subjects | 60 | (A) VR biofeedback<br>(B) 2D colored circle biofeedback | *Subjective measures*: relaxation, relaxation self-efficacy, mind wandering, focus on the present moment, attentional resources, experience enjoyment<br>*Objective measures*: HR, HRV (RMSSD, coherence ratio) | Attentional resource task, breathe following the rhythm of a pacer; attentional resource task | HR lower after session than before session in both conditions; relaxation higher after session than before session in both conditions; relaxation self-efficacy and focus on the present moment higher in VR biofeedback than 2D colored circle biofeedback; mind wandering lower in VR biofeedback than 2D colored circle biofeedback; coherence ratio and RMSSD higher during session in both conditions; experience enjoyment higher in VR biofeedback than 2D colored circle biofeedback |

(*continued on next page*)

**Table 2** (*continued*)

| Refs. | Design | Partic. | Experimental conditions | Measures | Task | Main statistically significant findings |
|---|---|---|---|---|---|---|
| (Bossenbroek et al., 2020) | Longitudinal, within-subjects | 8 | (A) VR biofeedback (6 sessions)<br>(B) control condition (no treatment)<br>The two conditions are alternated during four weeks | *Subjective measures*: anxiety, disruptive classroom behavior<br>*Objective measures*: none | (A) Maintain diaphragmatic breathing to move and explore freely the VE | Anxiety lower in overall VR biofeedback sessions than overall no treatment sessions; anxiety lower immediately after and two hours after session than before session in VR biofeedback |
| (Repetto et al., 2013) | Longitudinal, between-subjects | 25 | (A) VR biofeedback (8 sessions over an unspecified period)<br>(B) control condition (no treatment)<br>(C) VR without biofeedback (8 sessions over an unspecified period) | *Subjective measures*: anxiety<br>*Objective measures*: HR, SC | (A) Stay relaxed while observing the flickering campfire (Sessions 1,2), the waves lapping on a shore (Sessions 3,4), the waterfall (Sessions 5,6), stressful images (Sessions 7,8)<br>(C) as (A) | HR and anxiety lower after session than before session in VR conditions; anxiety lower after treatment than before treatment in VR conditions |
| (Scholten et al., 2016) | Longitudinal, between-subjects | 138 | (A) VR biofeedback (6 times during three weeks)<br>(B) control condition (platform video game, 6 times during three weeks) | *Subjective measures*: anxiety, anxiety-reducing expectations about the experience<br>*Objective measures*: none | (A) stay relaxed to evade a spirit, exit from a maze without hitting the walls with a ball, and win a hand-slapping contest<br>(B) play the platform videogame | Anxiety lower after treatment than before treatment in both conditions; linear decrease in anxiety higher in VR biofeedback than platform video game |
| (Blum et al., 2020) | Between-subjects | 72 | (A) VR biofeedback<br>(B) VR without biofeedback | *Subjective measures*: user experience, focus on breath<br>*Objective measures*: breathing activity, share (i.e., percentage of the total training session duration) of inhalations and exhalations, HRV (RMSSD, LF, HF) | Focus on breath and maintain slow diaphragmatic breathing | Focus on breath higher in VR biofeedback than VR without biofeedback; share of inhalations and share of exhalations higher in VR biofeedback than VR without biofeedback |

entire world respond to him/her. The user is told that in this way he/she can explore his/her abilities by first clearing the surrounding fog. After completing that task, the user is invited to perform other actions (touching the bush, releasing fireflies into the world) and tasks (making the night fall by relaxing). At the end of the experience, night comes, the fireflies fly away into the sky (Fig. 1f), and the voiceover concludes the story, informing the user that the experience is over and inviting him/her to return soon to the Archipelago.

### 3.2.1. *Structure of the VR experience*

The VR experience is organized into five phases:

1. System calibration
2. Clearing the fog
3. Interaction with the bush
4. Making the night fall
5. Finale

In the first phase, the system needs to be calibrated to the amplitude of the specific user's breathing by detecting the user's maximum and minimum expansion values. To this purpose, the experience begins with the voiceover that asks the user to take three deep breaths. Then, the system monitors all user's breaths for 60 s, storing the maximum and minimum expansion values detected by the sensor. During this time, two crystals in front of the user keep increasing their brightness until they emit some sparks at the end of the interval. Subsequently, a light trail sparks from the two crystals and moves to reach the different groups of crystals in the VE, brightening them. Then, to bring user's attention to the windmill blades and the foliage, the voiceover asks the user to observe their movement (Table 3), which from now on follows user's breathing.

In the second phase, the voiceover instructs the user about how to breathe slowly and deeply with the diaphragm and encourages him/her to do it to clear the VE of fog and maintain it clear. This task lasts for three minutes after which any remaining fog is cleared by the system to allow the user to move to the next phase.

In the third phase, the user hears the sound of rustling leaves coming from the bush at his/her right and the voiceover invites him/her to touch it. As the user touches the bush, fireflies come out of it and slowly fly near the user. If the user does not interact with the bush within 20 s, fireflies automatically come out of the bush to allow the user to move to the next phase.

In the fourth phase, the voiceover informs the user that sunset time is approaching and asks him/her to deeply relax to allow the night fall and then to keep the world in night conditions. The task lasts for three minutes after which night automatically takes over if the environment is not already in full night conditions.

The fifth phase marks the end of the experience and is meant as a final, emotion-evoking reward. The background music changes from calm to more lively, and the fruits on the trees light up. Additionally, light particles gently rise upward from all the crystals (Fig. 1e). Finally, the fireflies begin to fly skyward, leaving behind light trails in the night (Fig. 1f). While they are flying away, the voiceover tells the user they are saying goodbye, then it greets the user and invites him/her to return to the Crystals Archipelago soon.

During the VR experience, the voiceover subtly suggests which elements of the VE the user should pay attention to, but does not mention if and how physiological parameters control the movement or appearance of those elements. Table 3 contains those sentences of the voiceover that are used to direct user's visual attention.

## 3.3. *Biofeedback mechanisms*

The system receives physiological data recorded by a Thought Technology ProComp Infiniti encoder and processes them in real-time with a sampling rate of 10 Hz. An elastic girth sensor is placed over the user's abdomen to measure breathing activity; SC is recorded through a pair of Ag/AgCI electrodes placed in the center of the palm

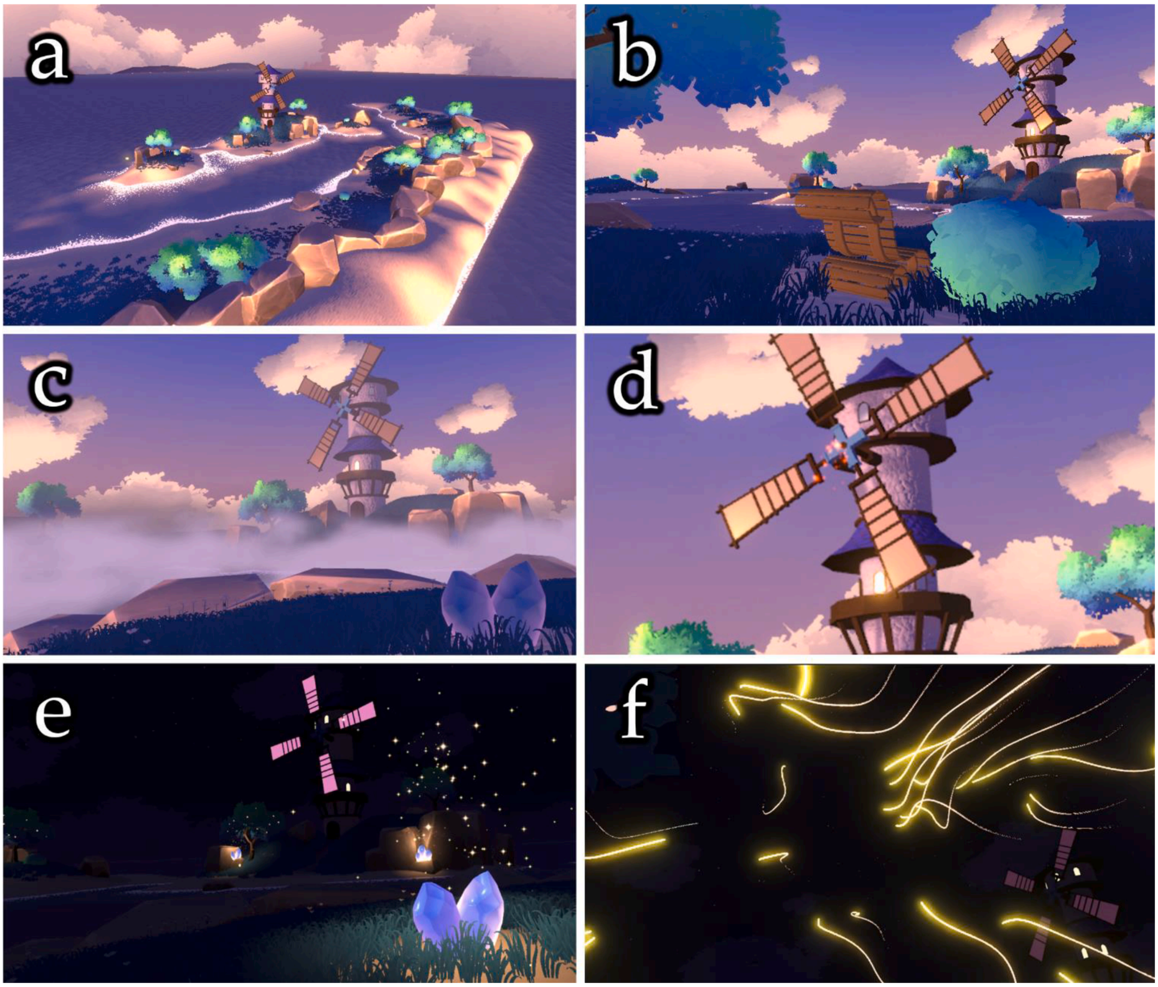

**Fig. 1.** (a) Scenery of the Crystals Archipelago; (b) The bench on which the participant sits during the entire experience; (c) Fog in the VE, as seen from the user's viewpoint; (d) Jamming of the windmill blades; (e) Fruits on the trees light up and light particles gently rise upward from all the crystals in the finale, as seen from the user's viewpoint; (f) Fireflies flying away and drawing light trails in the finale, as seen from the user's viewpoint.

and the carpus of the left hand, respectively; HR is recorded through a photoplethysmograph placed on the distal phalanx of the middle finger of the left hand. Multiple sensors are used to monitor whether the user is in a state of relaxation and capture different aspects of bodily responses. More specifically, breathing activity data is used to assess whether user's breathing is slow and deep, while electrodermal and cardiac activity data are used to detect whether user's SC and HR are low and/or decreasing. The proposed system employs biofeedback mechanisms, which involve measuring user's physiological signals and providing him/her with feedback: user's breathing activity, SC and HR affect the way the VE looks and behaves. Over time, the user could learn how to consciously control his/her physiological processes without the use of instrumentation. Table 4 provides an overview of the mappings we created for the VR experience.

### 3.3.1. *Breathing biofeedback*

Breathing data are normalized during the first phase of the VR experience so that the maximum and minimum abdomen expansion correspond to 1 and 0, respectively. If abdomen expansion during inhalation becomes higher than a threshold of 0.7, the inhalation is considered deep; if abdomen expansion during exhalation becomes lower than a threshold of 0.45, the exhalation is considered deep. Ten times a second, the rate of change of abdomen expansion is computed to determine whether user's breathing was slow by taking the two consecutive most recent breathing values, subtracting the older value from the more recent one, and dividing the result by the time elapsed between the two breathing values. If the result is lower than 0.7 during inhalation or 0.8 during exhalation, breathing is considered to be slow. The two values were empirically obtained by simulating a respiratory rate of 6 bpm, which is typically used in breathing training systems, e.g., in Chittaro and Sioni (2014a), Parnandi and Gutierrez-Osuna (2021, 2019). The thresholds are thus used by the system to determine if the user is breathing at a speed lower or equal to 6 bpm.

Once the user's minimum and maximum abdomen expansion values have been detected, the user can control the wind in the VE through his/her breathing activity until the end of the VR experience. Each time the user inhales, the leaves on the trees and bushes slow down their swing. When the user exhales, they swing faster up to a maximum value. If the user holds the breath, the swinging speed decreases until the leaves completely stop. Every exhalation is accompanied by the sound of wind blowing, which increases in volume if the exhalation is deep. The choice to map wind to breathing stems from the common experience that when an individual exhales, the produced air displacement feels like a light breeze. The visual feedback of leaves swinging is accompanied by congruent auditory feedback of wind blowing to enhance the sense of relaxation in the VE (Annerstedt et al., 2013).

The windmill blades behave similarly: the rotation speed of the blades depends on the speed of exhalation (the faster the exhalation, the faster the speed). The speed of exhalation corresponds to the rate of exhalation change, computed in the same way as the rate of change of abdomen expansion. In addition, as the rotation speed of the windmill blades increases during exhalation, the volume and pitch of the sound of

**Table 3**
Sentences from the voiceover that direct users' visual attention to specific elements. The voiceover was in Italian, all sentences have been translated here into English for reader's convenience.

| VR experience phase | Sentence |
|---|---|
| First phase | Hello, you are in the Crystals' Archipelago. This is a special place: here grow magical crystals that can synchronize with your vital spirit. You can see two of them right in front of you.<br>Oh, look! The crystals are activating! Your life spirit shines in the crystals and has reached every fiber of the environment. Observe the movement of the windmill blades. Also, observe the movement of the leaves of the trees around you. |
| Second phase | Breathe slowly and deeply to clear the fog that surrounds you, and try to keep the environment free from fog. |
| The first time the participant exhibits a respiratory rate above 6 bpm, from the second phase to the end of the fourth phase | Breathing too quickly damages the windmill. |
| Third phase | There seems to be something right in the bush near you. Touch the bush with your hand.<br>Also the fireflies are synchronized with you. Your energy flows in everything. |
| Fourth phase | Try to relax deeply to let the night fall. Then, try to maintain it. |
| Fifth phase | The fireflies are telling us that it is time to say goodbye. Goodbye, see you next time. |

the gears also increase up to a maximum value. On the contrary, during inhalations, the rotation speed of the blades slows down constantly, regardless of the speed of inhalation. This mapping of windmill blades uses a familiar pinwheel metaphor: the air produced by an individual during exhalation makes the pinwheel rotate, but the individual's inhalation does not affect the rotation of the pinwheel, which therefore slows down over time.

To indicate whether the user is performing slow and deep breathing, the windmill blades glow pink during a deep inhalation and yellow during a deep exhalation. In the literature, there are two studies that use color (Rockstroh et al., 2021) and lighting (van Rooij et al., 2016) of elements in the VE to differentiate between inhalations and exhalations, regardless of their depth. In our system, the color of the windmill blades changes only when breathing is deep, and discriminates between inhalation and exhalation, to help the user notice and distinguish deep breaths from more shallow breaths.

If the user is breathing faster than 6 bpm, meaning the rate of change of abdomen expansion exceeds the thresholds for inhalation and exhalation mentioned earlier, the windmill blades jam: they slow down abruptly, wobble and emit red sparks (Fig. 1d). This damage to the windmill blades sends a negative feedback to the user for breathing incorrectly. We have included it in the experience by following the operant conditioning paradigm (Staddon and Cerutti, 2003): to motivate users in performing the task correctly, in addition to audio-visual rewards when they maintain slow and deep breathing, this feedback plays the role of a mild punishment when they do not follow the recommended behavior.

During the second phase of the VR experience, the user performs the task of maintaining slow and deep breathing over time to clear the environment from fog. The system uses two parameters to determine fog behavior: distance of fog from the user, amount of fog in the environment. If the user takes a slow and deep inhalation followed by a slow and deep exhalation, during exhalation the two parameters continuously increase. Thus, the longer the exhalation, the larger the increase in distance of fog and the decrease in the amount of fog. If user's breathing is not deep or slow, the amount of fog increases while the distance does not change. In the literature, there are three studies that use a similar mapping: in Prabhu et al. (2020), the fog in the VE dissolves if the user maintains the breathing rate between 5.5 and 6 bpm for one minute; in Rockstroh et al. (2019), the sky clears of clouds if user's HRV value increases above a threshold value; in Gromala et al. (2015), the fog in the VE decreases as user's SC levels decrease and increases as they increase. Our system, as in Gromala et al. (2015), changes the amount of fog with each user's breath. In this way, the system helps users immediately understand if they are performing breathing properly, allowing them to correct their breathing patterns if necessary.

**Table 4**
Mapping of physiological parameters into VE elements.

| Parameter | Mapping in the VE | Related Refs. |
|---|---|---|
| Exhalation | *From the final part of the first phase until the end of the experience*: sound of wind blowing; increase in volume of the sound of wind if the exhalation is deep; increase in leaf swing of trees and bushes; increase in volume and pitch of the sound of windmill gears and rotation speed of windmill blades (the faster the exhalation, the faster the speed and the higher the volume and pitch); windmill blades glow yellow if the exhalation is deep<br>*During the second phase*: increase in amount of fog if the previous inhalation has not been slow or has not been deep; reduction in amount of fog and increase in fog distance from the user if a slow, deep inhalation is followed by a slow, deep exhalation | (Annerstedt et al., 2013; " Association for Applied Psychophysiology and Biofeedback," 2023; Gromala et al., 2015; Prabhu et al., 2020; Rockstroh et al., 2021, C. 2019; Staddon and Cerutti, 2003; van Rooij et al., 2016) |
| Inhalation | *From the final part of the first phase until the end of the experience*: decrease in leaf swing of trees and bushes; decrease in rotation speed of windmill blades (the longer the inhalation, the lower the speed); windmill blades glow pink if the inhalation is deep | (Rockstroh et al., 2021; Staddon and Cerutti, 2003; van Rooij et al., 2016) |
| Respiratory rate | *From the second phase until the end of the fourth phase*: red sparks come out of the windmill blades and windmill blades wobble if respiratory rate is greater than 6 bpm | (Staddon and Cerutti, 2003) |
| Rate of SC change (see Section 3.3.2) | *During the fourth phase*: change of sun and moon positions (the lower the rate of SC change, the lower the sun position until it disappears beyond the horizon and the higher the moon position, causing night to fall) | (Shaw et al., 2011) |
| HR | *From the third phase until the end of the fourth phase*: glowing rate of fireflies | (Gradl et al., 2018) |

### 3.3.2. SC biofeedback

During the fourth phase of the VR experience, the user relaxes to make the night fall. The system exploits a SC biofeedback mechanism similar to Shaw et al. (2011). In that system, as users relax and their SC thus decreases, the speed at which the sun moves across the sky is increased, until it sets beyond the horizon line, bringing the night. Then, the moon begins to rise, and a possible further decrease in user's SC causes an increase in the speed at which the moon moves across the sky until it reaches the zenith. If the user does not relax and thus his/her SC increases, the speed at which the sun (and then the moon) moves slows down and stops when it reaches the zenith.

Our system uses a similar biofeedback mechanism: a decrease in rate of SC change (which can be both positive and negative, computed in the same way as the rate of change of abdomen expansion) results in a decrease in the sun position towards the horizon until it reaches a minimum value, as well as a decrease in intensity (environment light originating from it) until the sun no longer contributes to VE illumination. Concurrently, the moon position rises towards the zenith until it reaches a maximum value, increasing in intensity. Conversely, an increasing rate of SC change leads to an increase in the sun position toward the zenith until a maximum value, along with an increase in intensity. Concurrently, the moon position decreases towards the horizon, diminishing in intensity.

#### 3.3.3. HR biofeedback

During the third phase of the VR experience, fireflies come out of the bush and fly around the user until the end of the fourth phase. User's HR is mapped directly into the glowing rate of fireflies. This type of visual feedback draws on a technique used in many first-person video games which fade a circular red transparent texture overlay in and out, following the rhythm of a heartbeat sound. In Gradl et al. (2018), this way of displaying user's HR with a glowing texture was the most effective for participants to accurately assess their HR, compared to two alternative visualizations.

## 4. Methods

### 4.1. Experimental design, research questions, and hypothesis

We conducted a between-subjects study, dividing participants into two groups. From now on, we will refer to the two groups as: (i) Biofeedback (BIO): the group of participants who tried the system with real biofeedback, i.e. they controlled the VE with their real-time physiological activity, and (ii) Sham (SHA): the group of participants who tried the system with sham biofeedback, i.e. changes in the VE were controlled by physiological data recordings from the session of another user, randomly selected from the BIO group.

We conducted the study to investigate (1) whether the proposed VR experience has relaxation effects and (2) to examine the possible role played by biofeedback on relaxation effects as well as on the sense of presence experienced by users.

We formulated the following hypotheses:

1. The VR experience relaxes users because the designed VE represents a natural scenario, and exposure to natural environments, both real (Berto, 2014; Kaplan, 1995) and virtual (Anderson et al., 2017; Annerstedt et al., 2013; Villani and Riva, 2012), can reduce stress and anxiety.
2. Biofeedback enhances the relaxation effect of the VR experience because participants in the BIO group receive real-time feedback on their physiological activity and this can help them in changing it, potentially achieving greater relaxation compared to users of the SHA group, which do not receive real feedback about their physiological performance.
3. Biofeedback increases sense of presence in the VE because changes in the VE that reflect physiological changes in the user may increase attractiveness of feedback (Rockstroh et al., 2019) and we posit that this could positively influence sense of presence perceived by users.

While immersive VR is known for its ability to induce a high sense of presence (Buttussi and Chittaro, 2018; Cummings and Bailenson, 2016; Makransky et al., 2019), little is known about the possible role of biofeedback in influencing sense of presence. In (Kosunen et al., 2016), an immersive VR-based biofeedback system achieved a greater sense of presence than immersive and non-immersive VR versions of the same system without biofeedback, but the difference was not statistically significant. Moreover, no study of sense of presence in biofeedback systems has considered a placebo (sham biofeedback) condition.

### 4.2. Participants

The study involved a sample of 35 volunteers (26 M, 9F) who received no compensation and were recruited through direct contact, email, and the social channels of our university. Their age ranged from 19 to 48 ($M = 26.60$, SD=7.23), and they were undergraduate students from different faculties or university employees. We asked participants if they were regular VR headset users and how much time they had used them: only two participants reported regular usage, with several hundred hours of use. All other participants reported instead between 0 and 80 h of use. Finally, we asked participants to complete the State-Trait Anxiety Inventory for Adults[1]: 20 items (STAI-S) assessed participants' current transient state of anxiety ($M = 32.31$, SD=5.42) while the other 20-items (STAI-T) assessed participants' relatively stable personality trait related to anxiety ($M = 40.66$, SD=9.38). Participants were assigned to two groups so that: (i) each group had a similar number of participants (BIO: $n = 18$; SHA: $n = 17$); (ii) the two groups were similar in terms of gender (BIO: 14 M, 4F; SHA: 12 M, 5F), age (BIO: $M = 26.50$, SD = 7.14; SHA: $M = 26.71$, SD=7.54), regular use of VR headsets (BIO: 1 "yes", 17 "no"; SHA: 1 "yes", 16 "no"), state anxiety (BIO: $M = 32.72$, SD = 6.27; SHA: $M = 31.88$, SD=4.51) and trait anxiety scores (BIO: $M = 40.39$, SD = 9.87; SHA: $M = 40.94$, SD = 9.13). Each of the two participants who were regular VR users was assigned to a different group. For the remaining group members, the average hours of VR headset usage were 3.06 (SD = 7.37) in BIO group and 5.63 (SD = 19.88) in SHA group. The lack of statistically significant differences between the two groups was confirmed by a Pearson Chi-square test for gender, and an independent $t$-test for age, hours of VR headsets usage, state and trait anxiety scores. The analysis excluded 4 participants due to VR headset shutdown ($n = 1$), artifacts in the recorded data caused by participant's cough ($n = 1$), and an unannounced fire alarm test in the university building during two sessions ($n = 2$). As a result, the analysis was conducted on 31 participants (BIO: $n = 16$; SHA: $n = 15$).

### 4.3. Ethical considerations

This study obtained research ethics approval from the Institutional Review Board of the Department of Mathematics, Computer Science and Physics at the University of Udine. Before beginning the study, all participants provided written consent for their involvement. Additionally, participants were verbally briefed regarding the anonymity of the data collected and the devices they were going to use in the study, i.e., VR headset and physiological sensors.

### 4.4. Measures

All questionnaires listed in the following were administered to participants through the PsyToolkit tool (Stoet, 2017, 2010).

#### 4.4.1. Subjective measures

We administered the previously mentioned STAI-S before and after

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[1] STAI-AD questionnaire: Copyright © 1968, 1977 by Charles D. Spielberger. Used with permission from the publisher (Mind Garden, Inc.)

the use of the system to measure the possible relaxation effects given by the VR experience. This scale includes 20 items and uses a 4-point Likert scale (1="not at all", 4="very much") to rate each response.

To measure sense of presence, we administered the Igroup Presence Questionnaire (IPQ) that asks participants to rate 14 items on a 7-point Likert scale, ranging from 0 to 6 (Schubert et al., 2001). The questionnaire includes a general item related to the sense of "being there", and three subscales for the independent dimensions of "spatial presence" (5 items), "involvement" (4 items), and "experienced realism" (4 items).

After the VR experience, we employed a customized biofeedback questionnaire inspired by the questionnaires in Chittaro and Sioni (2014b). Participants rated eight items on a 7-point Likert scale (1="not at all", 7="a lot") to assess perceived biofeedback quality (the first six items in Table 5) and the ease of performing the relaxation tasks of clearing the fog and making the night fall (the two last items in Table 5). Participants' ratings of the first six items were averaged to form a reliable scale of perceived biofeedback quality (Cronbach's alpha=0.76). Participants' ratings of the last two items were averaged to form a reliable scale of ease of performing the relaxation tasks (Cronbach's alpha=0.60).

The Positive and Negative Affect Schedule (PANAS) contains two scales, each comprising 10 items that measure the presence of positive (PANAS-PA) and negative emotions (PANAS-NA) (Watson et al., 1988). For each of seven specific moments of the VR experience they had tried, we asked participants to rate, on a 5-point Likert scale (1="very little or not at all", 5="a lot"), to what extent each PANAS item described how they felt. For each specific moment, a screenshot of that moment in the experience was shown to users for identifying it: beginning of the experience in the Crystals Archipelago, brightening of the crystals, task of clearing the fog, jamming of the windmill, first appearance of fireflies, task of making night fall, final departure of the fireflies. We used the difference between the PANAS-PA score and the PANAS-NA score concerning the two relaxation tasks of clearing the fog (Task1, hereinafter) and making the night fall (Task2, hereinafter) to assess whether the experience elicited positive emotions.

As a last step, each participant was briefly interviewed. The aim of the interview was twofold: obtaining insights from participants by allowing them to freely express their thoughts on the VR experience, and collecting feedback about how to improve the VR experience by investigating its strengths and weaknesses as perceived by participants. The interview process was structured into two parts. In the first part, the experimenter showed participants a grid of images containing all the screenshots used with the PANAS questionnaire and invited them to provide any comment they wished to make about the events depicted ("These are the images you saw in the questionnaire. Is there anything you would like to say about the events depicted?"). In the second part, participants were interviewed using a semi-structured approach, following the sequence shown in Fig. 2. If necessary, additional questions were asked to examine interesting aspects spontaneously raised by participants.

**Table 5**
Biofeedback questionnaire items. The questionnaire was filled out in Italian, all items have been translated here into English for reader's convenience.

| | |
|---|---|
| 1 | During the experience, I had the impression that I was controlling the wind with my breathing. |
| 2 | During the experience, I had the impression that the leaves of trees and bushes moved according to my breathing. |
| 3 | During the experience, I had the impression that the movement of the windmill blades followed my breathing. |
| 4 | During the experience, I had the impression that the glowing of fireflies was slower when I was more relaxed. |
| 5 | During the phase of the experience in which I had the task of clearing the fog, I had the impression that the fog cleared if I breathed slowly and deeply. |
| 6 | During the phase of the experience in which I had the task of making night fall, I had the impression that night fell when I relaxed. |
| 7 | During the phase of the experience in which I had the task of clearing the fog, I found it easy to maintain slow, deep breathing. |
| 8 | During the phase of the experience in which I had the task of making night fall, I found it easy to relax. |

### 4.4.2. *Objective measures*

The analysis of physiological data focused on Task1 and Task2. We used the Ledalab SC analysis software (Benedek and Kaernbach, 2010) to divide SC data into the tonic and phasic components, corresponding to skin conductance level (SCL) and skin conductance response (SCR), respectively. We then applied a Butterworth low-pass filter from the NeuroKit (Makowski et al., 2021) Python library to remove any artifacts. As suggested by Boucsein (2012), we calculated the mean value of SCL and the number of spikes per minute of SCR, considering an amplitude greater than 0.05 μS. Additionally, we used NeuroKit to compute respiratory rate (RR) from the recorded girth sensor data.

As mentioned in Section 3.3, the system records physiological data through a Thought Technology ProComp Infiniti encoder using an application that acquires the data in real-time with a sampling rate of 10 Hz. Since a sampling rate of 500 Hz is recommended for HRV analysis, and lower sampling rates can cause inaccuracy of HRV analysis (Merri et al., 1990), we also recorded cardiac activity at 500 Hz using a blood volume pulse finger clip sensor placed on the distal phalanx of the index finger of the left hand and connected to a BioSignalsPlux encoder. To compute HRV for analysis, we used the OpenSignals software ("OpenSignals," 2023). In particular, we derived the following three, highly correlated measures (Electrophysiology, 1996).: (i) the square root of the mean squared differences of successive NN intervals (RMSSD), (ii) the number of interval differences of successive NN intervals greater than 50 ms (NN50), (iii) the proportion derived by dividing NN50 by the total number of NN intervals (pNN50).

### 4.5. *Procedure*

The experimenter obtained written consent for participation in the study from participants, then briefed them about the anonymity of the collected data and informed them that the experience involved using a VR headset and physiological sensors. Then, participants were tested individually in a 50-min session. They sat on a swivel chair and filled the demographic, STAI-S, and STAI-T questionnaires. Participants were balanced in the BIO and SHA groups as described in Section 4.2. Both groups received the same information and followed the same procedure.

The experimenter applied physiological sensors to participants, helped them wear a Meta Quest 2 headset, and gave them one Quest Touch controller to hold with their right hand.

Participants were asked to choose a comfortable position. Then, they were immersed in a neutral VE representing a living room, while the baseline of physiological activity was recorded for three minutes. Afterwards, they tried the Crystals Archipelago experience that lasted 11 min.

After the experience, the experimenter helped participants remove the VR headset and physiological sensors and asked them to fill the STAI-S, IPQ, biofeedback, and PANAS questionnaires. Finally, they were interviewed for approximately five minutes, debriefed about the study, and thanked for their participation.

## 5. Results

All the analyses were conducted using SPSS version 28.0.1.0. Table 6 reports mean and standard deviation of all subjective measures for each group.

### 5.1. *STAI-S*

After checking the normality of the collected data, STAI-S scores were submitted to a 2 × 2 mixed design ANOVA, in which group served as the between-subject variable, and time of measurement (before and after the VR experience) served as the within-subject variable.

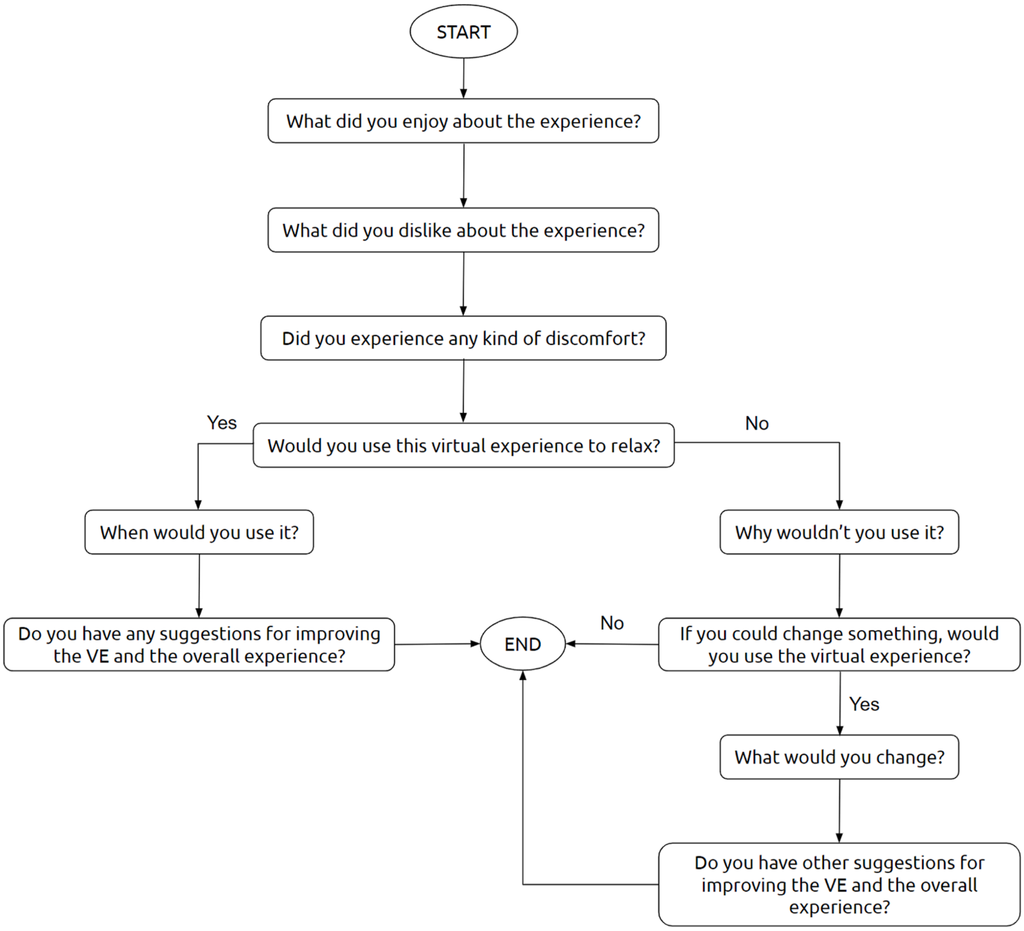

**Fig. 2.** Flow diagram of the second part of the interview. The interview was conducted in Italian, all sentences have been translated here into English for reader's convenience.

**Table 6**
Mean and standard deviation of all subjective measures for each group.

| **Measure** | **BIO** | | **SHA** | |
|---|---|---|---|---|
| | M | SD | M | SD |
| STAI-S before VR experience | 32.31 | 6.54 | 31.93 | 4.15 |
| STAI-S after VR experience | 24.75 | 3.57 | 28.53 | 5.71 |
| **Sense of presence** | | | | |
| IPQ total | 4.16 | 0.66 | 3.58 | 0.80 |
| Being there | 5.31 | 0.87 | 4.60 | 1.24 |
| Spatial presence | 4.86 | 0.77 | 4.15 | 1.33 |
| Involvement | 4.75 | 1.07 | 4.38 | 1.17 |
| Experienced realism | 2.39 | 1.18 | 1.82 | 0.89 |
| **Biofeedback questionnaire** | | | | |
| Perceived biofeedback quality | 5.57 | 0.80 | 4.22 | 1.15 |
| Ease of performing the relaxation tasks | 4.84 | 1.15 | 4.93 | 1.05 |
| **PANAS** | | | | |
| Difference between PANAS-PA and PANAS-NA in Task1 | 17.31 | 9.44 | 9.73 | 7.94 |
| Difference between PANAS-PA and PANAS-NA in Task2 | 16.50 | 12.19 | 13.80 | 9.32 |

Statistically significant results revealed a main effect of time of measurement, $F(1,29)=31.46$, $p < 0.001$, $\eta_p^2=0.52$, and a group by time of measurement interaction, $F(1.29)=4.54$, $p < 0.05$, $\eta_p^2=0.14$, as illustrated in Fig. 3. As suggested in (Cohen, 2008), we analyzed each simple effect using Bonferroni correction, considering the effects of time of measurement separately for each group and the effects of group separately at each time of measurement. STAI-S results showed a significant decrease in scores after the experience in both groups (BIO: $p < 0.001$; SHA: $p < 0.05$), and a significant difference in scores between the two groups after the experience ($p < 0.05$).

These results indicate that the VR experience influenced anxiety levels, as measured by the STAI-S questionnaire, with significant changes observed after the experience. Furthermore, there were significant differences between the two BIO and SHA groups, indicating that the effect of the VR experience on anxiety varies between these groups.

### 5.2. Physiological data

Kolmogorov-Smirnov normality test was performed on RR, SCL, SCR, RMSSD, NN50 and pNN50 data, collected during baseline, Task1, and Task2. Since in some cases RMSSD was not normally distributed, that data were log-transformed (in base 10), as indicated in (Cohen, 2008; Tabachnick and Fidell, 2007). Physiological data collected during Task1 and Task2 were submitted to two distinct 2 × 2 mixed design ANOVAs in which group served as the between-subject variable, and time of measurement (baseline and relaxation task) served as the within-subject variable.

In Task1, statistically significant results revealed a main effect of time of measurement on RR ($F(1,29)=240.07$, $p < 0.001$, $\eta_p^2=0.89$, Fig. 4a), SCR ($F(1,29)=59.77$, $p < 0.001$, $\eta_p^2=0.67$, Fig. 4c), RMSSD ($F(1,29)=9.14$, $p < 0.01$, $\eta_p^2=0.24$, Fig. 4e), and NN50 ($F(1,29)=4.67$, $p < 0.05$, $\eta_p^2=0.14$, Fig. 4h).

In Task2, statistically significant results revealed a main effect of time of measurement on RR ($F(1,29)=53.44$, $p < 0.001$, $\eta_p^2=0.65$, Fig. 4b), SCL ($F(1,29)=4,49$, $p < 0.05$, $\eta_p^2=0.13$, Fig. 4 g), SCR ($F(1,29)=46.60$, $p < 0.001$, $\eta_p^2=0.62$, Fig. 4d), and RMSSD ($F(1,29)=4.29$, $p <$

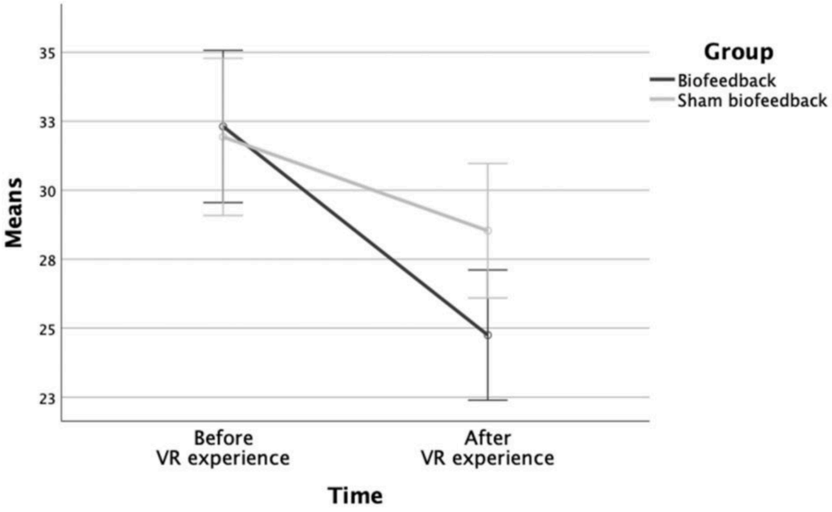

**Fig. 3.** Group by time of measurement interaction in STAI-S scores. Capped vertical bars indicate ± standard error (SE).

0.05, $\eta_p^2$=0.13, Fig. 4f). Moreover, a group by time of measurement interaction was found for RMSSD, F(1,29)=4,43, $p < 0.05$, $\eta_p^2$=0.13. The analysis of simple effects with Bonferroni correction revealed a significant difference between baseline and Task2 but only in the BIO group ($p < 0.05$) while no statistically significant differences were found between groups (Fig. 4f).

These results indicate that the VR experience had an impact at the physiological level. The differences observed after the VR experience indicate improvement in respiratory rate, skin conductance, and cardiac activity during both tasks. In addition, during Task2, a significant difference in cardiac activity, as measured by the RMSSD parameter, was found between the BIO and SHA groups.

### 5.3. Sense of presence

An independent *t*-test was used to compare sense of presence in the two groups (Fig. 5). The BIO group had higher IPQ total values than the SHA group. The difference between means was significant in the total IPQ score, t(29)=2.2, $p < 0.05$, two-tailed, Cohen's $d = 0.79$. No statistically significant differences were found for the subscales.

These results indicate that the BIO group reported a significantly higher sense of presence during the VR experience than those in the SHA group.

### 5.4. Biofeedback questionnaire

A Shapiro-Wilk normality test on the two scales of the biofeedback questionnaire indicated that data followed a Gaussian distribution. An independent *t*-test performed on the scale “perceived biofeedback quality” and the scale “ease of performing the relaxation tasks” revealed that the BIO group perceived a higher biofeedback quality than the SHA group, t(29)=0.21, $p < 0.001$, two-tailed, Cohen's $d = 1.37$ (Fig. 6a). No statistically significant differences were found between the groups on the ease of performing the relaxation tasks.

These results indicate that the BIO group perceived a higher quality of biofeedback than the SHA group, while both groups similarly perceived the ease of performing the two tasks.

### 5.5. PANAS

The mean scores of PANAS-PA felt by participants during the seven specific moments of the VR experience were higher than the mean scores of PANAS-NA. Negative emotions were generally higher in the SHA group than in the BIO group. All specific moments but one were shown to all participants during the experience: the exception is the windmill jamming that could occur from the second phase until the end of the fourth phase, because that event occurs only when user's physiological activity indicates fast and shallow breathing (BIO: $n = 7$; SHA: $n = 4$) so it was shown only to those users who experienced the event.

An independent *t*-test on the difference between PANAS-PA and PANAS-NA during the two tasks of relaxation revealed a statistically significant difference in Task1 between the BIO and SHA groups, t(29)= 2.41, $p < 0.05$, two-tailed, Cohen's $d = 0.87$ (Fig. 6b). No statistically significant differences were found for Task2.

These results indicate that participants predominantly reported positive emotions during the VR experience. However, the SHA group experienced more negative emotions than the BIO group. Furthermore, in Task1, the difference between positive and negative emotions experienced by the BIO group was significantly higher than the SHA group.

### 5.6. Interview

The collected interviews resulted in 120 min of audio recordings, which were thoroughly reviewed multiple times. Subsequently, the third author annotated participants' responses to each question and categorized responses across participants. The second author then checked the annotations and concurred with the response categorizations defined by the third author.

During the first part of the interview, four participants said they found the experience relaxing. Seven participants highlighted their enjoyment of the fireflies. Three of them reported they felt sad to see the fireflies fly away at the end of the experience. For instance, one participant stated, *“I really enjoyed the moment when I moved the bush with my hand and the fireflies came out, but I felt a little sad when they left”*. In contrast, one participant from the BIO group reported experiencing frustration and insecurity while performing the two relaxation tasks: although she thought she was following instructions well, she felt that the VE was not changing as she expected and had the impression that the VE was reflecting her own insecurity. For instance, she reported, “*Not being able to make the night fall or make the fog go away made me feel insecure and frustrated by my inability to do it*”.

In the second part of the interview, participants expressed appreciation for the following aspects of the experience: scenery (BIO: $n = 12$; SHA: $n = 12$), the two relaxation tasks (BIO: $n = 8$; SHA: $n = 5$), colors (BIO: $n = 1$; SHA: $n = 5$), fireflies (SHA: $n = 4$), storytelling (BIO: $n = 1$; SHA: $n = 2$) and virtual hand (BIO: $n = 2$).

The aspects of the experience that participants did not appreciate were instead: a feeling of not controlling the environment (SHA: $n = 4$),

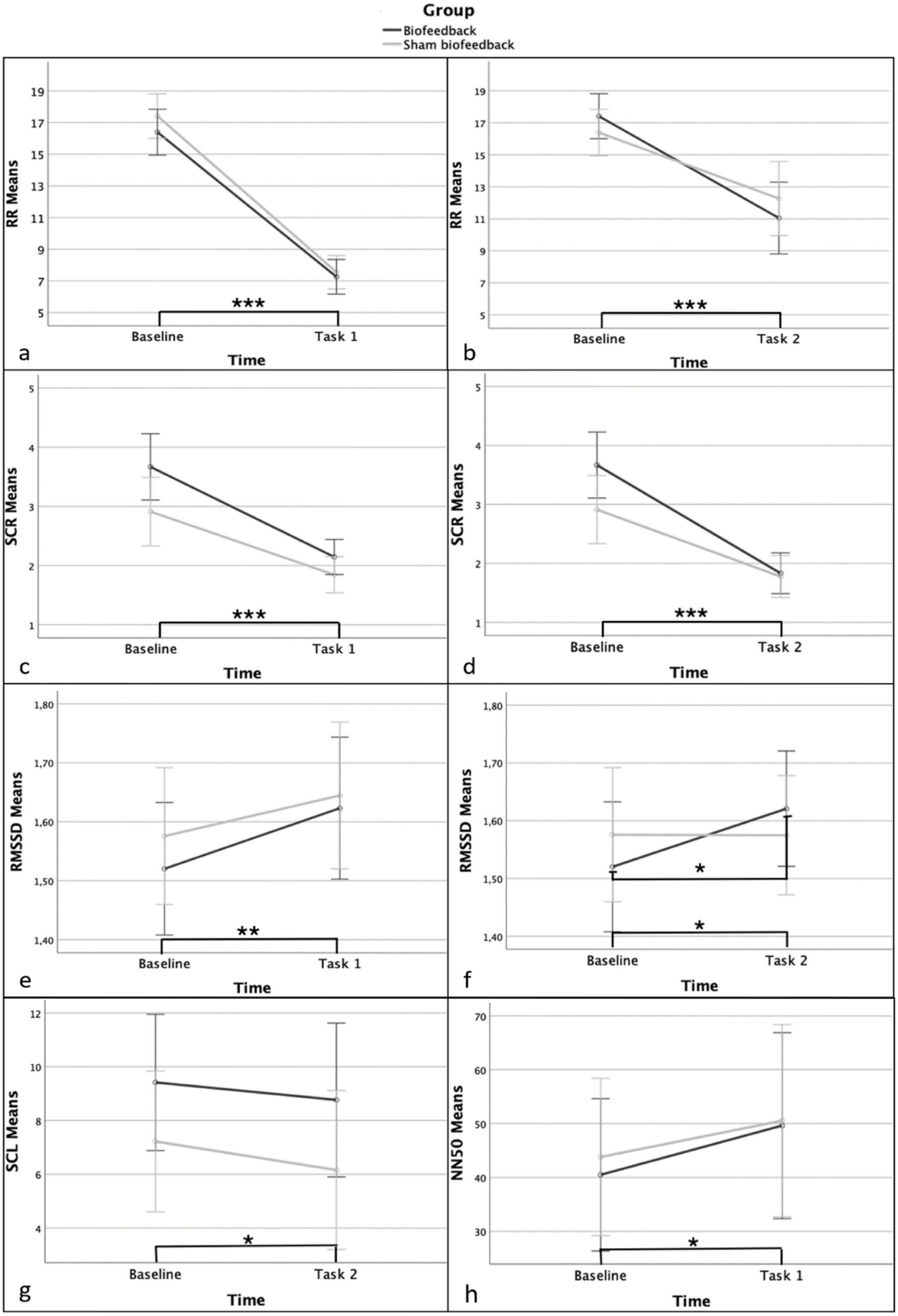

**Fig. 4.** Group by time of measurement in objective measures with statistically significant results. Capped vertical bars indicate ± SE. The *, **, *** signs indicate statistically significant differences with p-values respectively <0.05, <0.01, <0.001. A sign at the bottom of each chart indicates a main effect of time of measurement. a) RR, Task1; b) RR, Task2; c) SCR, Task1; d) SCR, Task2; e) RMSSD, Task1; f) RMSSD, Task2; the sign indicates a significant difference between baseline and Task2 in the BIO group; g) SCL, Task2; h) NN50, Task1.

a lack of interactivity (SHA: $n = 3$), low realism of the VE (BIO: $n = 2$; SHA: $n = 1$), the slow pace of Task1 (BIO: $n = 2$; SHA: $n = 1$) or of the whole experience (BIO: $n = 1$; SHA: $n = 1$), limited use of the hand controller (BIO: $n = 1$), and having only one hand in the VE instead of a full embodiment (BIO: $n = 1$; SHA: $n = 1$).

Some participants experienced discomfort when trying slow, deep diaphragmatic breathing because they found it difficult (BIO: $n = 1$) or because they did not understand whether they were performing it well (BIO: $n = 1$; SHA: $n = 3$).

Regarding the relaxation tasks, participants enjoyed the interaction controlled by the breath, and the nightfall. For instance, concerning Task1, one participant stated, "*I particularly appreciated the breath control*

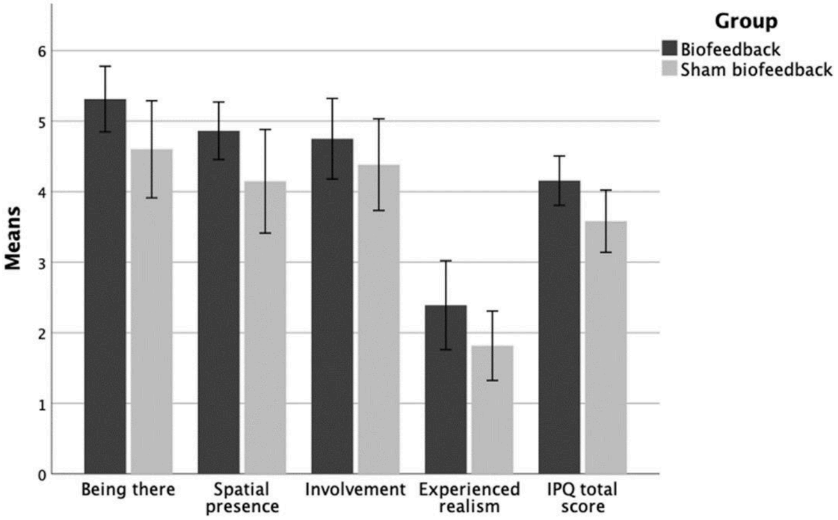

**Fig. 5.** Means of sense of presence. Capped vertical bars indicate ± SE.

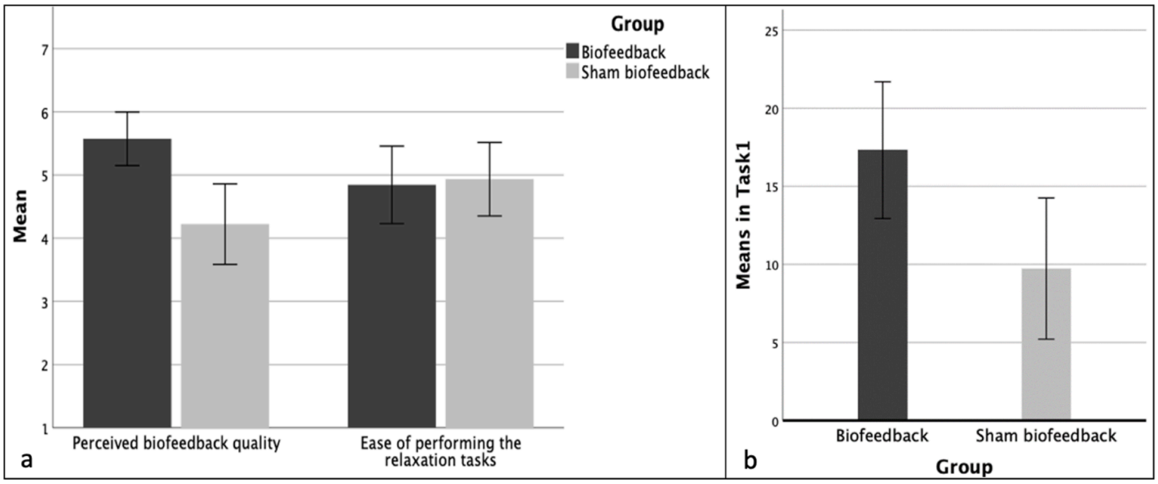

**Fig. 6.** (a) Means of scores of the biofeedback questionnaire. (b) Difference between PANAS-PA and PANAS-NA in Task1. Capped vertical bars indicate ± SE.

*exercise, as it made me aware of my abdomen's movement. I found it interesting that the environment reacted to my breath, so I appreciated the reaction of the fog to my breath"*. About Task2, one participant commented "*I liked the sense of calm and tranquility as the night fell; it let me relax and immerse myself more in the virtual environment.*" Critiques of the relaxation tasks primarily focused on Task1, which was perceived as too difficult or too lengthy. For instance, one participant stated, "*While I was breathing and I noticed the fog wasn't clearing, I wondered: will this fog ever go away?*".

Twenty-six participants would use the VR experience as a tool to relax (BIO: $n = 15$; SHA: $n = 11$). In particular, some of them would use it in the evening (BIO: $n = 8$; SHA: $n = 7$), to calm down and not think about problems (BIO: $n = 1$; SHA: $n = 3$), or before an exam or a deadline (BIO: $n = 1$; SHA: $n = 1$). Three participants said they would not use it (BIO: $n = 1$; SHA: $n = 2$), while two participants of the SHA group would use it only after some changes, i.e., a faster experience ($n = 1$) or a multiplayer mode ($n = 1$).

The most frequently mentioned suggestions for improvement were the following: allow moving around the VE (BIO: $n = 1$; SHA: $n = 2$), add more interactions (SHA: $n = 3$), decrease the duration of the experience (SHA: $n = 2$), and change the appearance of the bush (BIO: $n = 1$; SHA: $n = 1$).

## 6. Discussion

### 6.1. VR experience effects on relaxation levels

Results have confirmed our hypothesis that the VR experience relaxes users. The analysis of the STAI-S scores revealed that participants significantly decreased their level of anxiety after the VR experience. This is aligned with the results of Kaplan and Kaplan (1989), Kaplan (1995), where spending time in nature had positive effects on stress levels. Similarly, (Ohly et al., 2016; Valtchanov et al., 2010) found that natural virtual environments induced relaxation and restored attentional resources. The presence of "clouds, sunsets, and leaves moving in a breeze" in the VR experience may have contributed to participants' relaxation. Indeed, according to Kaplan and Kaplan (1989), such natural elements can stimulate fascination in individuals, thus improving the effectiveness of restorative experiences. The significantly improved level of relaxation in participants after the VR experience was also found in results obtained on objective measures: RR and SCR significantly decreased, and RMSSD and NN50 significantly increased during Task1, while RR, SCR, and SCL significantly decreased, and RMSSD significantly increased during Task2. These results obtained on breathing, cardiac, and electrodermal parameters are in line with those found in previous studies, where the exposure to VR-based biofeedback systems for relaxation training significantly increased HRV parameters (Blum et al., 2019; Rockstroh et al., 2019) or significantly decreased HR (Gorini et al., 2010; Rockstroh et al., 2019). Since diaphragmatic breathing stimulates relaxation (Fried, 1993; Ma et al., 2017), training participants to perform it during Task1 may have enhanced the overall level of relaxation achieved by them. Previous studies also showed that diaphragmatic breathing improves mood (Perciavalle et al., 2017), reducing stress and anxiety levels (Chen et al., 2017; Ma et al., 2017; Perciavalle et al., 2017). In our study, STAI-S scores highlighted a significant reduction in anxiety levels after the VR experience. This is in line with results found in previous studies on VR-based biofeedback systems for relaxation training (Blum et al., 2019; Gorini et al., 2010; Repetto et al., 2013; van Rooij et al., 2016), where the comparison of participants' self-reported state anxiety before and after exposure to the system resulted in a significant decrease in self-reported state anxiety. Finally, since in the final interview participants reported that they would use the system to relax ($n = 26$), we can conclude that they perceived the relaxation effect induced by the VR experience, and this can have contributed to their willingness to use the system again.

### 6.2. Biofeedback impact on relaxation

Results have confirmed our hypothesis that biofeedback enhances the relaxation effect of the VR experience. More precisely, the analysis of the STAI-S scores revealed that the BIO group achieved a significantly lower level of anxiety than the SHA group after the VR experience. Moreover, the analysis of the objective measures found that RMSSD significantly increased in the BIO group but not in the SHA group during Task2. When evaluating biofeedback systems for relaxation training, comparing real biofeedback with a placebo condition is necessary to determine the role that biofeedback actually played. However, only two previous studies in the literature evaluated a VR-based biofeedback system for relaxation training by comparing real and sham biofeedback (Chittaro and Sioni, 2014b; Tinga et al., 2019). One of the studies used non-immersive VR and focused on comparing two algorithms for stress detection, only one of which performed significantly better than sham biofeedback (Chittaro and Sioni, 2014b). The study did not analyze relaxation effects and performed statistical analysis only on a questionnaire that assessed the biofeedback quality perceived by participants. In our study, the biofeedback quality perceived by participants was positively influenced by real biofeedback. This finding can be attributed to the proposed visual and auditory biofeedback mechanism used in the VR experience. Such feedback facilitated participants in the BIO group to perceive the effects of their physiological activity in the VE, which is important for reinforcement learning (Gaume et al., 2016). Ease of performing the relaxation tasks was instead perceived similarly by both groups, which achieved relatively high values.

The second study that considered a placebo condition focused on relaxation (Tinga et al., 2019), and concluded that sham biofeedback was better than real biofeedback, resulting in a lower HR. The disparity between this finding and ours could be explained by the extreme differences between their system and our system. In Tinga et al. (2019), the system consisted of an empty immersive VE that only displayed a cloud whose movements towards and away from the user were controlled by the user's breathing, whereas in the placebo condition, the cloud moved back and forth every three seconds. As illustrated in detail in Section 3, our system provides instead a much more complex, natural VE where rich biofeedback influences different elements of the VE through various mechanisms and using multiple physiological parameters. While simple forms of biofeedback stimuli may carry the risk of becoming monotonous (Huang et al., 2006; Soyka et al., 2016), this risk can be reduced by feedback that results in various changes to a natural VE, which could improve motivation and reduce distractions (Rockstroh et al., 2019). Moreover, proceeding through the various steps of the narrative that our system provides could keep user's curiosity and attention alive, and also be rewarding. Moreover, our system associated Task1 and Task2 with two different rewards: achieving a clear sky and a beautiful nighttime setting, respectively. Overall, the VR experience elicited positive emotions in participants, as shown by the PANAS results. Although the windmill jamming was an element of the experience designed as negative feedback, the PANAS results found that seeing the windmill jam during the VR experience ($n = 11$) made participants feel mostly attentive and alert. This finding is in line with the operant conditioning paradigm (Staddon and Cerutti, 2003): to prevent the occurrence of the aversive feedback (the windmill jamming), participants might have improved their concentration to better perform the recommended behavior (slow breathing in this case). The difference between PANAS-PA and PANAS-NA experienced during Task1 was significantly greater for the BIO group than the SHA group. Since breathing can be consciously controlled and was used to perform the task of clearing the fog, participants in the SHA group were likely less helped because they could not see stimuli in the VE that fully corresponded to their real breathing activity. This may have provoked greater negative emotions and fewer positive emotions compared to the BIO group. Indeed, the final interview highlighted that sham biofeedback decreased the degree of satisfaction with the VR experience: all participants who explicitly described their dissatisfaction with poor interaction with the VR environment ($n = 3$) or felt unable to control the VR environment ($n = 4$) belonged to the SHA group. Additionally, the two participants who would have preferred a shorter duration of the experience also belonged to the SHA group. This suggests the possibility that the SHA group experienced more feelings of boredom than the BIO group, and this difference is due to the absence of real biofeedback that allows for greater motivation and focus during the VR experience (Rockstroh et al., 2021). In addition, three out of four participants who said they had difficulty understanding if they were performing the task correctly belonged to the SHA group. This is consistent with the role of biofeedback in helping participants improve their sense of control over the VR environment and their physiological parameters.

### 6.3. Biofeedback impact on sense of presence

Results have confirmed our hypothesis that biofeedback increases sense of presence in the VR experience.

We found a statistically significant result regarding sense of presence, where the IPQ total score was higher with real biofeedback than with sham biofeedback. In both groups, sense of presence scores were high (between 4 and 6 in a 0 to 6 scale) for the sense of being there as well as for spatial presence and involvement subscales. Only realism scores were low in the two conditions, but this was expected, given the design choice to use simple fantasy graphics. The present study extends previous results on biofeedback and presence by considering a VR placebo condition. A previous study found that an immersive VR-based biofeedback system obtained higher sense of presence than both immersive and non-immersive VR versions of the same system without biofeedback, but the difference in sense of presence felt by participants with the three versions of the system was not statistically significant (Kosunen et al., 2016). In our study, the higher sense of presence felt by the BIO group rather than the SHA group may have also influenced the result obtained with the PANAS, where the difference between PANAS-PA and PANAS-NA experienced was significantly higher in the BIO group than the SHA group. Since the BIO group experienced a greater sense of presence, and affective state can be influenced by presence (Riva et al., 2007), this may have led to a greater emotional impact on the BIO group than the SHA group.

### 6.4. Final considerations and limitations

In summary, our study showed that the VR experience improved the level of relaxation in both groups. Specifically, real biofeedback produced better results than sham biofeedback in terms of both relaxation and sense of presence. These results highlight the importance of the role that biofeedback can play in VR-based relaxation training systems to increase sense of presence felt by users and to achieve higher levels of relaxation than those that would be obtained using the same system without biofeedback. Future VR systems for relaxation training should consider integrating biofeedback to maximize their efficacy. Moreover, such systems should be designed to engage and stimulate users. The variety and complexity of the VE, responsive to users' physiological activity, can keep users' attention and improve motivation during the experience. Moreover, it is crucial to underscore the importance of evaluating the effectiveness of VR-based biofeedback systems by considering a placebo condition involving sham biofeedback to assess the true impact of the biofeedback.

A limitation of our study is that it was conducted on a small predominantly male sample. Several studies show that females tend to report greater levels of anxiety (McLean and Anderson, 2009) and higher intensities of emotional experience (Grossman and Wood, 1993; Hess et al., 2000) than males. Therefore, male predominance in our sample might have attenuated the intensity of measured anxiety. Replicating the experiment with a gender-balanced sample might thus produce higher anxiety values and provide a more accurate representation of anxiety experienced across genders.

Moreover, it should be noted that our study was not focused on identifying which specific aspect of the VR experience had the greatest impact on our outcomes. Further research should investigate the individual contributions of the visual and auditory elements of the VR experience, the two relaxation tasks, and the role of storytelling, to better understand how each of these aspects contributed to the relaxation effects experienced by participants.

Furthermore, our study did not assess the duration of the relaxation effect after the VR experience and did not explore its potential longitudinal effects. A previous study has shown that users can improve their diaphragmatic breathing over time, thereby achieving deeper relaxation (Rockstroh et al., 2021). Additionally, Bossenbroek et al., found that the use of the VR-based biofeedback system described in (van Rooij et al., 2016) induced relaxation in a clinical sample that persisted for approximately two hours (Bossenbroek et al., 2020). Future studies should therefore extend our single-session study to a longitudinal study with multiple training sessions to investigate the duration of relaxation effects and other possible long-term effects.

## 7. Conclusions

In this paper, we proposed a novel VR-based biofeedback system for breathing and relaxation training. The system aims at teaching users how to perform slow and deep diaphragmatic breathing by immersing them in a natural VE that changes based on multiple physiological measurements. A narrative that unfolds in multiple stages engages the user as the main character of a story that evolves also through the performance of two main activities required to advance the narrative. We assessed the actual contribution of biofeedback by comparing the results of a group of participants who used the system with real biofeedback to a placebo group who used the system with sham biofeedback. The results showed that the proposed system helped participants to relax in both groups. Moreover, biofeedback led to greater relaxation as well as greater sense of presence than sham biofeedback. These findings underline the value of adding biofeedback to VR-based systems for relaxation training, while also reiterating the importance of including placebo control conditions in studies evaluating biofeedback systems.

The present study focused on a single session of the proposed system. Our next step will be to design a longitudinal study with multiple training sessions to investigate possible long-term effects on relaxation, and conduct the study on a clinical sample. The rich and varied VR experience might promote prolonged use of the system, helping users voluntarily change their physiological parameters until, over time, these changes might be maintained without the need of being helped by the system. The VR experience of the proposed system provided two relaxation activities controlled by biofeedback based on user's breathing and SC, while it did not include relaxation activities controlled by biofeedback based on cardiac parameters. Biofeedback based on HRV has been shown to be effective in prevention and treatment of anxiety and stress (Goessl et al., 2017), and previous studies on systems using HR-based biofeedback (Repetto et al., 2013) or HRV biofeedback (Blum et al., 2019; Rockstroh et al., 2019) have shown that such VR-based biofeedback systems relaxed participants. Future work will consider enriching the VR experience by designing a new relaxation task controlled by biofeedback based on HR or HRV, taking into account existing research based on cardiac parameters (Blum et al., 2019; Gorini et al., 2010; Repetto et al., 2013; Rockstroh et al., 2019; Scholten et al., 2016; Schuurmans et al., 2015) to further enhance the relaxing effect of the proposed system.

## CRediT authorship contribution statement

**Luca Chittaro:** Conceptualization, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. **Marta Serafini:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yvonne Vulcano:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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