RESonance: Lightweight, Room-Scale Audio-Visual Biofeedback for Immersive Relaxation Training

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ABSTRACT Biofeedback systems enable the users' awareness of their internal health status by displaying their physiological signal, and further facilitate them to move toward self-regulation and behavior change. Single-modal biofeedback display can provide clear yet less engaging physiological information; a multi-modal, immersive display could provide more engaging user experiences, but such a biofeedback system is relatively difficult to deploy. To strike a balance between engagement and ease of deployment, we present *RESonance*, a lightweight, immersive audio-visual biofeedback system for relaxation training. The system informs the users about their internal states (i.e., breath and heart rate variability) through ambient mediums, i.e., ambient light and nature soundscape, which can be provided by a lightweight infrastructure. The results of a 24-participant user study suggest that the system not only efficiently supports breathing regulation in relaxation training but also offers immersive and engaging user experiences.

INDEX TERMS Biofeedback, relaxation training, audio-visual interface, ambient light, nature soundscape, immersive experience.

I. INTRODUCTION

According to the survey '*Stress in America*' conducted by the American Psychological Association [1], an increasing number of people are suffering from chronic stress in their everyday life. The stressors vary widely from finances and work to discrimination and unhealthy lifestyles. Our body often overreacts to these everyday stressors. The 'always-on' stress responses may produce excess stress hormone, causing an imbalance of autonomic nervous system [2]. Chronic stresses put individuals at an increased risk of numerous health problems, including depression [3], immune dysregulation [4], heart disease and hypertension [5]. A new crop of mind-body techniques has been used to improve the autonomic balance and mitigate the harmful effects of stress on our health. Common mind-body practices include diaphragmatic breathing [6], yoga [7], meditation [8] and biofeedback-assisted relaxation training [9].

Biofeedback is a unique mind-body technique that brings unconscious physiological processes under conscious control. Biofeedback instruments use various bio-sensors to measure bio-signals from the user's body and present the information about his/her internal states through
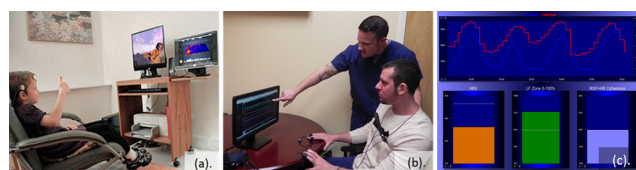

FIGURE 1. (a). A typical biofeedback-assisted training in the therapy room (b). with the assistance of a well-trained therapist (c). a traditional graphic user interface of the biofeedback system.

external displays. Biofeedback allows users to observe the adverse impacts of stress on their physiology and further facilitates them to learn self-regulation skills to cope with stress and achieve relaxation more efficiently. In clinical settings, biofeedback training [10] is typically performed in a therapy room with the assistance of a well-trained therapist as shown in Fig 1. The clinical biofeedback systems generally use a graphic user interface (GUI), e.g., in [11], [12], to present feedback information in a clear and precise manner. However, in everyday use, such displays have a high barrier to non-specialist users and seem less engaging for relaxation training in non-clinical contexts, such as at home or in the workplace.

Many studies [13], [14] have shown that the user experience with mind-body techniques can be crucial to the outcomes of relaxation training. A meditative or immersive experience may facilitate a state of mindfulness and help users improve their engagement in relaxation training. Thereby, the immersiveness has been explicitly addressed in many interactive systems for relaxation. For instance, *Sonic Cradle* [15] invites the user into a chamber of complete darkness and creates a meditative experience with a soundscape responding to his/her respiration. *ExoBuilding* [16] makes the user immerse in a semi-closed, shape-changing space where the light, sounds and the spatial structure are manipulated to represent multiple types of biofeedback information for facilitating relaxation training.

Recently, Virtual Reality (VR) techniques have been extensively applied to human-computer-interaction (HCI) for enhancing user engagement and facilitate an immersive experience. VR-based biofeedback systems are therefore becoming increasingly common. For instance, *DEEP* [17] provides immersive breathing biofeedback through a VR game which situates the user in a virtual underwater environment. The mindfulness training with *Inner garden* [18] leverages a tangible artefact, spatial augmented reality and VR headset to provide a playful and engaging experience. However, such an immersive biofeedback system has a high adaption threshold and deployment cost. It is relatively difficult to deploy in everyday environments due to the specified requirements on spatial room structure, new hardware, and operating configurations. To our knowledge, most of the immersive biofeedback systems are only evaluated and applied within a laboratory context.

To strike a balance between engagement and ease of deployment, we design *RESonance*, a lightweight, room-scale audio-visual biofeedback system for relaxation training. The *RESonance* system harnesses ambient lights and nature sounds to create an immersive environment where users can know about their physiological states in real time. On one hand, as a biofeedback interface, *RESonance* presents heart rate viability (HRV) data to help users learn and practice self-regulation (i.e., resonance breathing [23]) for relaxation. The design principle of 'natural coupling' [19] was employed in interface design to provide a gentle-yet-intuitive representation of biofeedback. On the other hand, we assume the stimuli of coloured light and nature sounds may lead to an enhanced relaxation effect. The three main contributions of this work are:

- Developing an immersive biofeedback system that leverages ambient lights and nature soundscape to present biofeedback information and shape an engaging user experience for relaxation training.
- Employing the principle of 'natural coupling' in interface design for an intuitive understanding of the biofeedback data.
- Evaluating the system in a 24-participant user study.

The remainder of this paper is organized as follows. In the next section, we present related work about heart rate variability biofeedback, new forms of biofeedback interfaces, and ambient displays with lights and nature sounds. We then proceed to describe a detailed framework of *RESonance* system and the design of mapping from the bio-data to the parameters of light and sound for biofeedback display. Finally, we present the results of the evaluation and discuss the feasibility of *RESonance* biofeedback system regarding its user experience and training effectiveness for stress relief and relaxation.

II. RELATED WORK
A. HRV BIOFEEDBACK FOR RELAXATION
Heart rate variability (HRV) refers to the variation of time intervals between adjacent heartbeats. Our heartbeat is regulated by the autonomic nervous system (ANS), where its sympathetic branch accelerates and parasympathetic branch decelerates the heart rate, thus producing a complex and ongoing pattern of HRV [20]. Our body responds to stress through the ANS. Therefore, in long-term ambulatory recordings, HRV can be used as a stress indicator, assessing the effects of stress on our physiology [21]. A high HRV normally indicates a healthy autonomic balance and a good resistibility of the human body to stress. A low HRV indicates an autonomic imbalance towards sympathetic dominance, which may lead to excessive 'stress hormone' disrupting various physiological processes and interfering with the homeostasis.

On the other hand, HRV can be improved by deep breathing. Heart rate varies in synchrony with respiration, by which inter-beat intervals (IBI) is shortened during inhaling and prolonged during exhaling [22]. An individual's IBI data can be modulated into a stable and sine-wave-like pattern by 'resonant breathing', at which the HRV will be increased to its maximum value [23]. The research [24] suggests that the practice of resonant breathing can reduce the stress responses of ANS and help to restore autonomic balance. Therefore, during relaxation training with resonant breathing, the real-time feedback of IBI data can assist the users to learn resonant breathing skills and the feedback of short-term HRV can serve as an outcome measure, indicating users' performance, primarily related to their breathing regulation.

B. BIOFEEDBACK IN NEW FORMS
Recently, many efforts from HCI field have been devoted to creating new forms of biofeedback with various new interactive technologies. The biofeedback data can be conveyed with a metaphorical visualization [25], a piece of music [26], [27], [49], a soundscape [15], light [28], [29], [50], and serious games [30], [31]. Different from a clinical biofeedback display that focuses on accuracy and timeliness, these new interfaces were designed to make the feedback more intuitive to understand and the systems more comfortable to use. Therefore, a casual form of biofeedback might be better suited for relaxation training in everyday context. For instance, a music-based biofeedback system [26] was designed to facilitate drivers to cope

with stress during driving. Lighting biofeedback enables users to perform breathing training with less restriction of the place [28]. A playful biofeedback game was designed specifically for children with ADHD to practice deep breathing [30].

C. MULTIMODAL BIOFEEDBACK DISPLAY

Multimodal displays came to be widely used in biofeedback systems with two primary purposes: to enhance information perception and to enrich sensory experience. Multimodal displays may improve user perception of the feedback due to the distribution of information processing [32]. The provision of information through a combination of audio and visual modalities can improve the usability of the interface. For instance, biofeedback data can be presented by on-screen graphics with an audio tone as an augment [11]. The portable device of *emWave2* uses an indicator light coupled with an audio cue to present the value of the coherence between respiration and heart rhythm [12]. On the other hand, the stimuli from a multimodal interface may enrich and enhance sensory experience aiming to promote relaxation. Besides the above examples of *ExoBuilding* [16] and *Inner Garden* [18], Muller *et al.* [33] used an interactive video and soundscape to facilitate embodied experience. Djajadiningrat *et al.* [34] developed a biofeedback system named *Breathe-with-the-Ocean*, providing a relaxing experience with the audio, visual (light) and haptic (tactile) stimuli.

D. AMBIENT DISPLAY WITH LIGHTS AND NATURE SOUNDS

Light, as an integral part of daily life's settings, can serve as an ambient medium to present digital information and enhance immersion. As an alternative to on-screen visualizations, ambient lighting display can be aesthetically pleasing, decorative, and unobtrusive without burdening the user. For instance, a *MoodLight* [35] that presents users' arousal data may cultivate healthful self-awareness in home settings. Biofeedback through ambient light places minimal constraints on users, which may offer a more comfortable condition for relaxation training [28]. On the other hand, light as an environmental stimulant has a particular ability to provoke emotional and physiological responses. Ross *et al.* [36] reported a cool color light (green, blue, indigo) could reduce an individual's physiological arousal level and improve subjective feelings of calmness. A lighting environment with meticulously-set light color and intensity shows a mood-enhancing or relaxation effect. For instance, *Philips luminous textile* uses the coloured light creating a 'De-stress' waiting areas in the hospital to help the patients feel energized and relaxed. In recent years, coloured light therapy [37], [38] has been increasingly practiced by many clinicians to assist in stress relief, relaxation training and the treatment of psychosomatic disorders.

Nature sounds are often used in ambient displays and peripheral interactions. Nature sounds are quite common, among 'everyday sounds' around us, so they are more likely to be understood intuitively and be 'nestled' among an indoor acoustic environment seamlessly. One famous example might be *AmbientROOM* [39], which modulates the volume and density of bird and rainfall sound to indicate the number of unread email messages and the value of a stock portfolio. Moreover, nature sounds also show a healthful effect, helping people fall asleep, reduce stress and boost moods [40]. People enjoy walking on forest paths, listening to the sounds of birds, or sitting under the eaves and listening to the music of rain. The birdsong and sound of rain have shown a positive emotional effect [41]. A mixture of sounds from a fountain and tweeting birds have also demonstrated stress-relieving effect via the autonomic nervous system [42].

Above studies have shown the beneficial effects of ambient light and nature sounds for both information displays and relaxation, but few studies have explored using light and nature sounds as an ambient medium to convey physiological data for biofeedback. No study has been known to the authors to elaborately combine ambient light and nature sounds as a multi-modal biofeedback interface, creating an immersive user experience for relaxation training. Our study serves as an exploration of designing such a system.

III. RESonance BIOFEEDBACK SYSTEM

In our view, biofeedback interfaces that support relaxation training should take an 'ambient' form beyond a GUI interaction paradigm. A variety of ambient mediums may serve as biofeedback interface to present physiological data and also as an environmental stimulant to foster the experience of immersiveness and relaxation. With *RESonance*, we explore audio-visual biofeedback with the ambient light and nature soundscape which can be deployed in a living space or home environment seamlessly.

A. PHYSIOLOGICAL DATA FOR BIOFEEDBACK

In this study, *RESonance* is interfaced with an HRV biofeedback system, where two types of physiological data are presented: inter-beat interval (IBI) and short-term HRV. Both IBI and HRV are calculated from the blood volume pulse (BVP) signal, which is measured by a noninvasive photoplethysmograph (PPG) sensor on the finger. Firstly, the BVP signal is processed with peak detection algorithm into the time series of IBI. The IBI data are presented back to users immediately to guide them in breathing regulation. A specially modified form of the standard deviation of IBI data (SDNN) is calculated with a moving window of 16 heartbeats as the index of short-term HRV. The $SDNN_{16}$ is calculated with the following formula: $SDNN_{16} = (15 \times SDNN_{16} + |IBI - IBI_{avg}|)/16$, and $IBI_{avg} = (15 \times IBI_{avg} + IBI)/16$. The $SDNN_{16}$ value is updated with each heartbeat.

B. DESIGN RATIONALE

The initial intention of the study was to bring the well-proven clinical biofeedback techniques down to everyday life so that non-expert users can self-use it for relaxation training at home or office environment. Briefly, we expect

that the *RESonance* system ought to be informative for assisting self-regulation and also to provide an immersive experience facilitating relaxation. The biofeedback display of *RESonance* is designed with the following three primary considerations.

1) IMMERSIVENESS IN SIMPLICITY

For everyday use, we think an immersive biofeedback system needs to meet the requirement of lightweight infrastructure and low deployment cost. In our design, the *RESonance* system harnesses ambient lights and a synthesized nature soundscape to turn a home or office environment into an immersive biofeedback interface. The implementation of *RESonance* requires only a set of lights at different distances to the user and a public speaker in the room. We suggest utilizing the existing home structures (e.g., walls and corners) and the spatial distribution of lights to shape a semi-closed space. By shining the ambient light onto distant walls, the reflected light becomes softer and more diffused, filling the field of view. The setup of the lights can be adjusted to different room structure.

2) INFORM THROUGH BOTH CENTER AND PERIPHERY OF ATTENTION

As described above, the *RESonance* system presents both IBI and HRV data. The instantaneous feedback of IBI data aims to guide users in breathing regulation. And the feedback of short-term HRV informs the users about the results of relaxation training. Due to the different roles, the IBI and HRV data need different levels of the user's attention. Therefore, *RESonance* works on the principle of *Calm Technology* [43], the display of IBI and HRV data are distributed to the center and the periphery of user attention respectively. The IBI data are presented by the dynamic changes of lights and wind sound to take the center of attention. In contrast, the HRV data are coupled with the saturation of the light color and the overall quietness of the soundscape, in which way the changes of light and sounds are perceived subtle and slow, to reside at the periphery of user attention. The further details about the parameter mapping in the interface are provided later.

3) NATURAL COUPLING BETWEEN THE DATA AND INTERFACES

A set of distributed lights can offer rich parameters for information display, including the optical parameters like brightness, hue, and saturation and dynamic ones like the interactions between different lights. A nature soundscape that consists of various sounds offers even more audio parameters, such as volume, frequency, or reverb effect. Therefore, selecting appropriate parameters to couple with biofeedback data is an important design consideration. The representations of IBI and HRV data in *RESonance* were designed by following the idea of 'natural coupling' suggested in [19] and [34]. Based on our previous studies [25], [44], we suggest that a natural coupling between biofeedback data and interface expressions may help users understand the data's meaning and facilitate their self-regulation by mirroring the

expressions of the interface. For instance, in [25], we focused on the creation of a metaphor in mapping design. We used an image of tree or flower as a visual metaphor to represent healthy or unhealthy states of users. The semantic relevance between the physiological data and its representation helps to interpret the physiological implications. In [44], we used the inflation and deflation of an airbag as a metaphor of lung's movement during breathing to provide breathing guidance. The natural coupling between the shape changes of the interface and the user's chest movement facilitates breathing regulation.

The same thinking goes for the design of *RESonance* display. To make the IBI and HRV data intuitively understandable, we selected different metaphors for lighting and audio interfaces. Breathing is a process of gas exchange. To present the IBI data for breathing guidance, the lighting interface 'transfers' the brightness back and forth between the center and ambient lights to simulate the airflow with breathing movements. As an individual inhale, the air is breathed into the body, and the brightness is transferred to the center light close to the body. Conversely, on exhale, the air is expelled from the body, and the brightness is transferred to the ambient lights far from the body. In the audio interface, we use the changes of wind volume to present the IBI data. As the user inhales, the wind sound in the soundscape becomes quiet. As the user exhales, the wind becomes loud.

In relaxation training, the HRV data carries the physiological meanings about relaxation level. As a cool-toned light is commonly associated with the calmness, we use a blue-green color to indicate an improved HRV. When the user achieves a better relaxation, the lights will become a more saturated blue-green. In the audio interface, we apply a model of nature soundscape as described by [45]. The model suggests that multiple types of nature sounds can work together to 'inform' the listener through an intuitive perception of the whole nature soundscape, such as quietness and richness. We use the quietness of nature soundscape to present the HRV data. In such a way, an improved HRV will drive the nature soundscape to become quiet and simple. We assume the quietness of soundscape could be naturally associated with a peaceful and relaxed state.

C. SYSTEM IMPLEMENTATION

Fig 2 shows the framework of *RESonance* biofeedback system. The blood volume pulse (BVP) signal is measured by a PPG sensor and transmitted to the *RESonance* biofeedback program. Then, the BVP signal is processed into IBI and HRV data that are coupled with the audio and lighting parameters. The *RESonance* biofeedback program is implemented on a *Processing*[1] platform. The lighting system includes a set of programmable light bulbs produced under the *HUE*[2] brand by *Philips*. In the sound synthesis procedure, the biofeedback data modulate the parameters of the selected audio contents
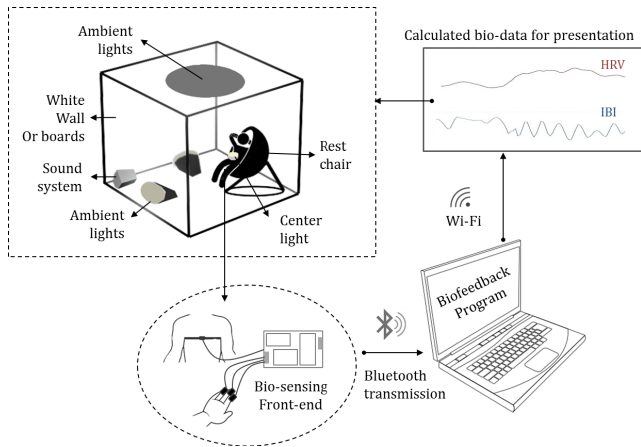
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[1] https://www.processing.org/
[2] https://www.developers.meethue.com/

FIGURE 2. The framework of *RESonance* biofeedback system.

FIGURE 3. Mapping from IBI and HRV to lighting parameters.

with *Beads* Java audio library. Finally, the nature soundscape and the lighting environment in the room are modulated by the updates of the IBI and HRV data in real time.

IV. PARAMETER MAPPING

The mappings between the biofeedback data (IBI and HRV) and the parameters of lights and nature soundscape are shown in Table 1.

TABLE 1. Parameter mapping for biofeedback display.

Bio-data	Sound parameters	Lighting parameters
IBI (450-1250ms)	Volume of Wind sound	Brightness value of centre light (0-255) ambient lights (255-0)
SDNN$_{16}$ (0-225ms)	Quietness of Nature Soundscape	Saturation of centre and ambient light (0-255)
	Richness of Nature Soundscape	

A. MAPPING TO LIGHTING PARAMETERS

In the lighting interface, the IBI data (450 to 1250 ms) is mapped to the value of brightness parameter from 0 to 255 (maximum) for the ambient lights and from 255 to 0 for the center light. Thus, the center light turns bright during inhalation and turns dark during exhalation. The ambient lights behave the opposite way, as shown in Fig 3. The hue value is set to a fixed value of 45000 (blue-green), and the saturation value (0 to 255, maximum) is coupled with SDNN$_{16}$ (0 to 225ms). In the relaxation training, an improved HRV with the deep breathing will lead to a blue-green color with high saturation.

B. MAPPING TO THE PARAMETERS OF SOUNDSCAPE

In the nature soundscape, the IBI data is presented by the wind sound, and the HRV data is presented by the quietness and richness of the soundscape. The wind sound is generated
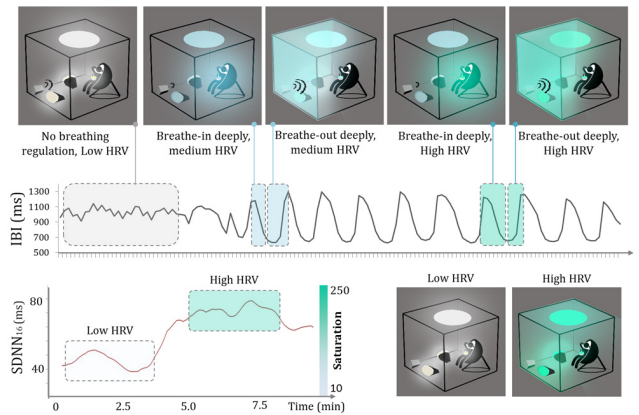
with the *windnoise* function provided by *Beads Java* audio library. The direction of the wind sound is adjusted with *windnoise.pan* function to switch between the left and right channels with a random frequency from 5 to 10 seconds. The intention here is to improve the reliability of the wind sound. The IBI data directly controls the addition and reduction to the basic volume of the wind. Specifically, the IBI data (450 to1250 ms) are mapped to the amplification factor of the wind sound from 0 to 0.1. When an individual inhales, the IBI data decreases and the wind becomes quiet. Conversely, on exhale, the wind becomes loud.
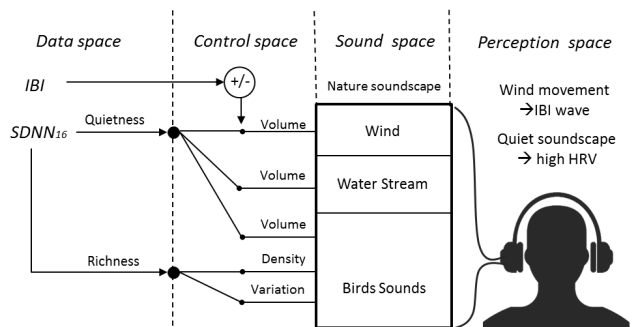

FIGURE 4. Mapping from IBI and HRV to audio parameters.

As shown in Fig 4, SDNN$_{16}$ (0 to 225 ms) is negatively coupled with the water volume, and the volume, density, and variations of the bird sounds. Firstly, the volume of the selected audio contents was normalized into the same modest value by the sound editing software. The SDNN$_{16}$ is mapped to the amplification factor of the volume of water and bird sounds from 0 to 0.1. The mapping from the SDNN$_{16}$ to the density and variation of bird sounds are more complex. The bird sounds in the soundscape are very short and can be regarded as the discrete tonal events. The SDNN$_{16}$ is mapped to the playing frequency of bird sound from 30 sounds/min to 10 sounds/min.

The nature soundscape contains five types of bird sounds that are rated as the most likely to help people relax and

recover from mental fatigue (i.e. silvereye, wren, greenfinch, collared dove and cuckoo). Each type of bird sound contains five samples with some variations. As such, there are in total of 25 bird sound samples in the soundscape library. Each time the bird sound is being played, the $SDNN_{16}$ determines the range of the sample selection (25 to 5 samples). An improved $SDNN_{16}$ will lead to a small range of selection. Therefore, when the $SDNN_{16}$ value increases with deep breathing, the volume, density, and variation of the sounds will be reduced. According to the perceptual model described by [45], the nature soundscape will be perceived to be a quiet and simple environment, which is similar to a blue-green light indicating a good result of relaxation training.

V. EVALUATION

The purpose of the user study is to evaluate the effectiveness of *RESonance* biofeedback system for relaxation training. A within-subjects experiment was conducted with the participants experiencing resting, stress and relaxation sessions. After the baseline measurement at rest, the participants underwent a stress-inducing task before the relaxation session. The experiment hypothesises that the relaxation with audio-visual biofeedback from *RESonance* can help users to reduce physiological arousal, facilitate deep breathing and enhance heart rate variability. Meanwhile, we also investigated the user experience by collecting and analyzing the qualitative data of follow-up interviews.

A. PARTICIPANTS

A total of 24 participants (14 males, 10 females) aged from 23-34 ($M = 27.6$; $SD = 2.97$) were recruited for the study. All participants are researchers or Master students at the University. All participants reported no history of diagnosed cardiac or psychiatric disorders. Participants who were technically unable to use the biofeedback system were excluded from the trial. All participants gave the written informed consent.

B. SETTING UP

A relaxation space was designed to simulate a home environment for the setup of *RESonance* biofeedback system. The windows of the room have shutters to darken the room. We made a curved 'wall' with several square wooden boards whose surfaces are matte white. It shapes a semi-enclosed space with an adjacent white wall of the room. Within the space, there is an armchair, a bio-sensing device, three lights and a sound speaker. The wireless speaker is placed behind the whiteboard in front of the chair. As shown in Figure 5, the center light is a wireless and portable lamp which can be held in hands. The ambient lights consist of two lamps on the floor shining on the whiteboards. These lights highlight the relaxation space to separate it from the rest of the room.

C. PROCEDURE

The experiment lasts for about 45 minutes and consists of three stages. Each stage lasts 10 minutes. All three stages were introduced and explained first. Before the experiment, the participant experienced a short trial of the *RESonance* biofeedback system. In stage 1, the participant was seated quietly for baseline collection. In stage 2, the participant was asked to perform two stressful tasks for inducing the stress responses. Then in stage 3, the participant performs relaxation training with *RESonance* biofeedback system. For each stage, we collected the participant's physiological data and the self-reports on anxiety and relaxation level. At the end of the experiment, we conducted a follow-up interview to collect qualitative data about the user experience.

D. SIMULATED STRESSORS

In stage 2 of the experiment, we combined a Stroop color-word test [46] and a mental arithmetic test [12] as an acute time-limited stressor to induce the psychophysiological stress responses. In the arithmetic test, the participants were required to get a higher score as quickly as possible. The whole stress session lasted 10 minutes. Only when the participants passed the Stroop test, they can start the arithmetic test.

E. BIOFEEDBACK PROTOCOL

In stage 3, the participants relaxed with *RESonance* system. The working of *RESonance* system and HRV biofeedback were explained as follows: *"The brightness of the lights and the wind sound are controlled by your heart beats intervals. When you breathe in, the center light turns bright, the ambient lights turn dark, and the wind sounds quiet. When you breathe out, the ambient lights turn bright, the center light turns dark, and the wind becomes loud. You can make the brightness transfer between the center and the ambient lights periodically by regulating your breath. When you achieve the resonant breathing, the color of the light will be getting closer to blue-green and nature soundscape will be getting quiet and simple."*

F. MEASUREMENTS
1) PHYSIOLOGICAL DATA

The physiological measures include skin conductance responses (SCRs), respiration rate (RSP-R) and the index of heart rate variability (HRV-LF%). The physiological data were recorded in all three stages by using the *Nexus-10*[3] device (*MindMedia, the Netherlands*). A respiration strap sensor was placed on the abdomen across the participant. The strap sensor was adjusted so that there was a slight tension when the participant fully breathed out. Two electrodes of the skin conductance sensor were strapped on the finger pads of the middle and ring fingers of the left hand. The sensors were placed on the palm side of the finger. The IBI data is calculated from the BVP signal and then analyzed in *Kubios*[4] software to obtain the HRV index, the percent of power in low frequency (HRV-LF%). RSP-R was derived from the

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[3]Nexus-10, *https://www.mindmedia.com/en/products/nexus-10-mkii/*
[4]Kubios HRV software,*https://www.kubios.com/*

respiration trace. The skin conductance data was analyzed in *Ledalab*[5] software. The continuous decomposition analysis (CDA) performs a decomposition of SC data into continuous signals of phasic and tonic activity. We calculated the amount of skin conductance response (SCRs) as one index of arousal.

2) SELF-REPORT ON ANXIETY AND RELAXATION

After each stage, we collected the participant's self-report on anxiety and relaxation experience by the Relaxation Rating Scale (RRS) and state anxiety subscale of the State-Trait Anxiety Inventory (STAI-S). The RRS [47] is a simple self-reported instrument that requires the participant to rate his/her level of relaxation on a Likert-type scale with one being 'not relaxed at all' and nine being 'totally relaxed.' The STAI-S [48] is a 20-item self-report survey, which requires the participants to rate how they feel 'at this moment.' Higher scores indicate a greater level of anxiety and stress.

3) INTERVIEW

At the conclusion of the experiment, a semi-structured interview was conducted to collect the qualitative data regarding the users' opinions on the audio-visual biofeedback with ambient light and nature soundscape. The interview focused on three themes with a pre-determined set of open questions as listed in Table 2. There was enough space for the participants to feedback on their experience freely. Interviews were transcribed verbatim and thematically analyzed. Additionally, the frequency of statements attributed to themes was scored to indicate relative importance. The interview data was used to support the interpretation of the quantitative data.

TABLE 2. The list of questions for the interview.

Theme	No.	Interview Questions
Room scale interface	Q1 Q2	*What did you (not) like/dislike about the overall experience during the relaxation training in the RESonance biofeedback room?*
Lighting interface	Q3	*To what extent did you notice the changes of the lights?*
	Q4 Q5	*What did you (not) like about the experience with the lighting environment?*
Audio interface	Q6	*To what extent did you notice the changes of the nature soundscape?*
	Q7 Q8	*What did you (not) like about the experience with the nature soundscape?*

VI. RESULTS

A. QUANTITATIVE RESULTS

Table 3 provides an overview of the descriptive statistics for physiological measures. The Shapiro-Wilk test indicated the physiological measures were not statistically normal in all stages. Therefore, a nonparametric

[5]Ledalab software, *http://www.ledalab.de/*

TABLE 3. Descriptive statistics of physiological measures for each of the three stages (columns). The Median is listed with Range, as well as Min and Max values and P-value of the Shapiro Wilk test is listed (SW Sig).

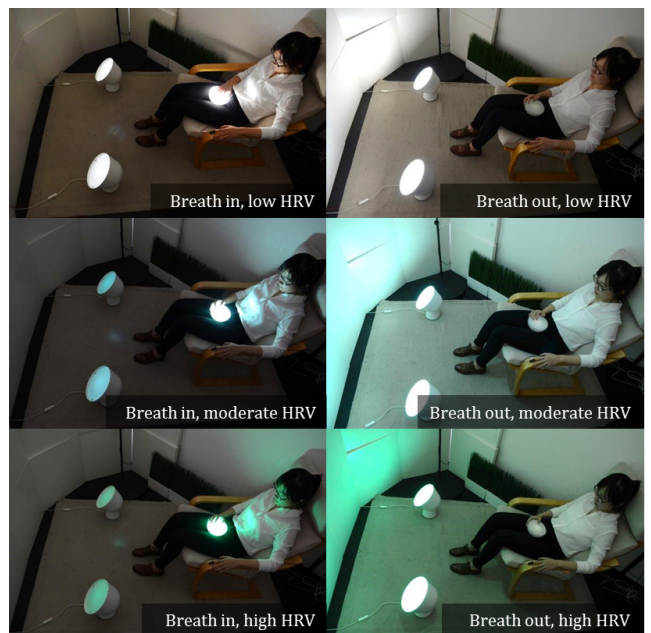| Conditions		Baseline	Stress	Biofeedback
SCRs	Median	3.25	7.8	2.85
	Range	14.3	10.2	8.5
	Max	14.5	12.8	8.7
	Min	0.2	2.6	0.2
	SW Sig	.006	.936	.205
RSP-R	Median	18.38	20.35	6.66
	Range	16.82	35.55	14.92
	Max	26.62	22.42	18.72
	Min	9.8	13.13	3.8
	SW Sig	.892	.042	.000
HRV-LF%	Median	0.55	0.51	0.875
	Range	0.63	0.55	0.68
	Max	0.8	0.86	0.97
	Min	0.16	0.3	0.29
	SW Sig	.857	.570	.001

FIGURE 5. A user performs relaxation training with the *RESonance* Biofeedback system in the room.

Friedman test was conducted to test the differences between three stages. Post hoc analysis with Wilcoxon signed-rank test was conducted to identify which stages differed significantly.

1) REScnance REDUCES PHYSIOLOGICAL AROUSAL

The SCRs value may indicate the physiological arousal and stress level. Figure 6 shows the changes in SCRs during the stress stage and the biofeedback stage (relative to the baseline measurements). Due to the stressful task, most participants showed an increase in SCRs compared to their baselines. During the biofeedback stage, for most participants, their SCRs were reduced lower than the ones in the stress stage and

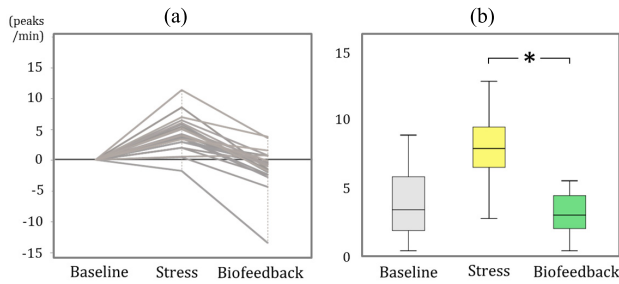**FIGURE 6.** SCRs changes and the boxplots for SCRs in the three stages.

FIGURE 8. HRV changes and the boxplots for three stages.

even the baseline stage. The results of a Wilcoxon Signed-rank test show a significant difference ($Z = -4.26, p < 0.01$) in SCRs between the biofeedback stage ($Mdn = 2.85, SD = 1.96$) and the stress stage ($Mdn = 7.80, SD = 2.46$). The results are suggestive that the biofeedback through lighting and nature soundscape was effective in reducing the arousal level after the stress.

2) RESonance FACILITATES DEEP BREATHING

Figure 7 shows the changes in respiration rate (RSP-R) during the stress stage and biofeedback stage (relative to the baseline). During the biofeedback relaxation, the RSP-R was significantly slower than the stress stage and the baseline stage. A Wilcoxon Signed-rank test shows that the RSP-R was reduced significantly in the biofeedback stage ($Mdn = 6.66, SD = 3.4$), compared to the stress stage ($Mdn = 20.35, SD = 5.68; Z = -3.31, p < 0.05$) and the baseline stage ($Mdn = 18.38, SD = 4.61; Z = -4.29, p < 0.01$). The results indicate that the HRV biofeedback through the *RESonance* system is effective in facilitating the deep breathing during the relaxation training.
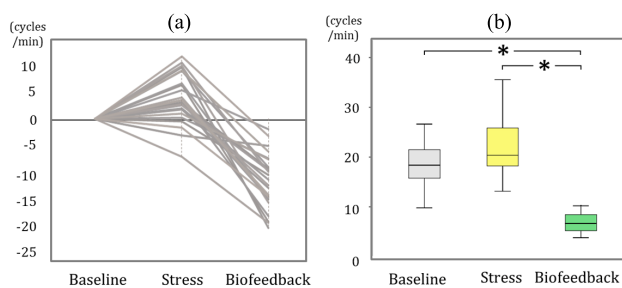

FIGURE 7. RSP-R changes and the boxplots for three stages.

3) RESonance ENHANCES HEART RATE VARIABILITY

Figure 8 shows that the changes in HRV-LF% during the stress and the biofeedback stages (relative to the baseline). The HRV-LF% was significantly increased in the biofeedback stage ($Mdn = 0.875, SD = 0.169$) compared to both of the stress stage ($Mdn = 0.51, SD = 0.149; Z = -3.97, p < 0.01$) and the baseline stage ($Mdn = 0.55, SD = 0.156; Z = -4.17, p < 0.01$). The short-term HRV can be
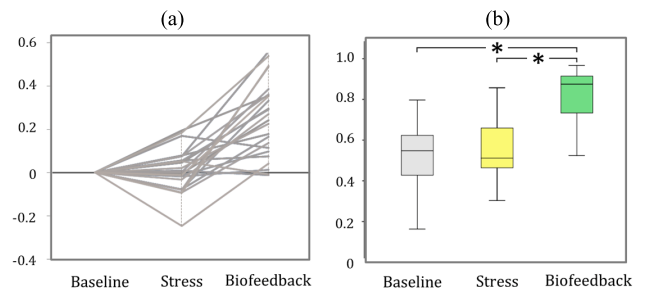
highly related to the respiratory cycle of the participants [23]. Especially when the user achieves her/his 'resonant' breathing around 10s per circle, the power spectrum of LF band will burst around 0.1Hz. The results of the HRV-LF% are consistent with the respiration results, indicating that the *RESonance* system can help the users to enhance their HRV by regulating their respiration into an optimal pattern (i.e., resonant frequency).

4) RESonance REDUCES SUBJECTIVE ANXIETY

The results of Relaxation Rating Scale (RRS) and State-Trait Anxiety Inventory (STAI) surveys are shown in Figure 9. Regarding the RRS, the median RRS for the baseline, stress and biofeedback stage were 7 (6 to 8), 4 (3 to 5.75) and 8 (7 to 8), respectively. The RRS was significantly increased in biofeedback stage vs. stress stage ($Z = -4.3, p < 0.01$). Regarding the STAI, the median STAI for the baseline, stress, and biofeedback stages were 36 (30 to 38), 47 (38 to 57) and 31 (27.25 to 34.75), respectively. The results of a Wilcoxon Signed-rank test show the STAI was significantly decreased in the biofeedback stage vs. the stress stage ($Z = -4.28, p < 0.01$), and the baseline stage ($Z = -2.78, p < 0.01$).
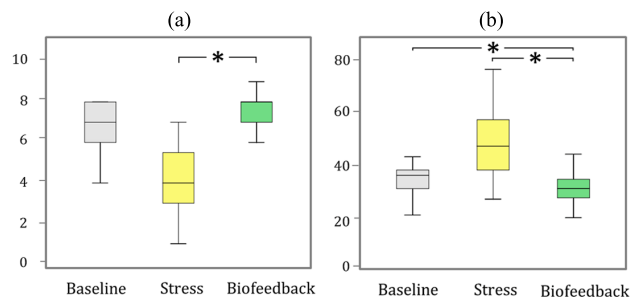

FIGURE 9. Boxplots of the RRS and STAI results.

B. INTERVIEW RESULTS ABOUT USER EXPERIENCES

1) THEME 1: RELAXING AMBIENCE CREATED BY RESonance

The responses indicated that the room-scale *RESonance* interface provided a relaxing and immersive experience for most participants. 14 participants (out of 24) mentioned that the

'semi-enclosed' space helped them concentrate during the relaxation training. 22/24 stated that the blue-green coloured light created a calming and relaxing ambience. 13/24 suggested that an immersive exposure to the blue-green light and nature sounds made them "*feel calm and peaceful*" (P3), "*seem to be more stable and tranquil*" (P21), and "*feel like in a forest with many birds and a water stream far away*" (P10). Besides, 11/24 suggested that the light from multiple sources (reflected from the whiteboards and handheld lamp) created the sense of space and a feeling of immersion. For instance, one participant mentioned, "*I enjoy being surrounded by these lights, this light (the center light) keeps me focused*" (P3).

2) THEME 2: LIGHTING ENVIRONMENT AND ITS USER EXPERIENCE

The responses indicated that the lighting interface was effective in presenting IBI and HRV data. All participants stated that the brightness changes of the lights were easy to perceive. 20/24 stated that the IBI feedback presented by 'brightness transfer' between the spacial lights was easy to understand for breathing guidance. For instance, some participants mentioned that "*the center light is very helpful to me, when it became totally dark, I started to breathe in. When it became to the brightest, I breathe out*" (P20) and "*I learned to breathe deeply to see an obvious brightness transfer*" (P14). 15/24 stated that manipulating the brightness transfer between the center and ambient lights was engaging. For instance, one participant described "*the transfer of brightness engaged me to regulate my breathing. When I breathed in, it felt like all the energy was absorbed and gathered around me. And when I breathed out, it felt like I was releasing energy to lighten up the room*" (P14). However, 3 out of those stated that they felt tired and dizzy because they attempted to breathe deeper.

22/24 stated that the color changes of the lights were easy to perceive and effective in informing them about the results of the relaxation training. When the lights turned to blue-green, they felt satisfied. Moreover, when the lights turned to white, they felt motivated to regulate their breathing. For instance, some participants mentioned that "*I felt satisfied when the color became green because I knew I was doing well.*"(P11), and "*the green light seemed like a reward for my breathing regulation*" (P1). However, 9 out of the 22 mentioned that a sudden change from green-blue to white would make them confusing or tense. For instance, some participants mentioned "*I was very relaxed, but the lights turned white, this made me confusing*" (P24) and "*Sometimes I was tired of breathing deeply, so I just relaxed and breathed naturally. Then I found the light got white quickly; this gave me some pressure*" (P7).

3) THEME 3: NATURE SOUNDSCAPE AND ITS USER EXPERIENCE

Regarding the audio display, the responses indicated that the quietness of the nature soundscape could effectively indicate the training result, same as the color of the light. 13/24 mentioned that the audio feedback through the nature soundscape was essential because, in most of the time, they did deep breathing with eyes closed. Like one participant described "*when the light became blue or green, I closed my eyes and kept breathing deeply. When the nature sounds were getting noisy, I opened eyes and regulated my breathing with the feedback from the light*"(P21). 19/24 stated that the change of quietness was easy to identify through the loudness and frequency of birds or the loudness of water. 23/24 stated that the created nature soundscape was relaxing and pleasant. 13/24 mentioned that the selected nature sounds shaped an acoustic nature environment, which was associated with some relaxing natural scenery. 7 out of the 13 also mentioned that the various bird sounds made the relaxation training more interesting.

VII. DISCUSSION

A. LIGHTWEIGHT DESIGN FOR IMMERSIVE RELAXATION TRAINING

In this study, we were seeking the alternatives to the traditional GUI-based biofeedback for an immersive relaxation training. Without using a VR device [17], [18]and or a functional physical space [15], [16], *RESonance* offers a home-based lightweight solution to strike a balance between an immersive experience and ease of deployment. The home setting is a relaxing place for most of us. With the popularization of the Internet of Things (IoT), a 'smart home' offers increasing ambient media to inform and interact with its inhabitants. We think the *RESonance* interface can be seamlessly embedded in a real home based on a wide range of intelligent lights (e.g., *Philips Hue*) and intelligent speakers (e.g., *Google Home*,[6] *Apple HomePod*,[7] *Amazon Echo*[8]). A smart home speaker can fill the room with immersive 360° audio and provides an augmented soundscape. An intelligent lighting system may color the home, lounge room and even office, turning it into an immersive luminous space.

B. NATURAL COUPLING FOR BIOFEEDBACK INTERACTION

The essence of biofeedback is the information that is measured from the human body and fed back to the user self. Based on different interactive media, how to represent the biofeedback data meaningfully and pleasantly is a key design issue regarding Human-Computer Interaction (HCI). The *RESonance* system leverages ambient light and nature soundscape as the interactive media for biofeedback display. In this paper, we introduced the idea of 'natural coupling', which is from the interaction design framework proposed in [19] and [34]. Different from tangible products emphasizing 'natural coupling' between the appearance, the user's action and the device's reaction for intuitive interaction, here we suggest that a natural coupling between biofeedback data

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[6]https://store.google.com/?srp = /product/google_home
[7]https://www.apple.com/homepod/
[8]https://en.wikipedia.org/wiki/Amazon_Echo

and interface expressions. Similar to our previous work, we used a metaphor to address natural coupling in mapping design. For instance, we used the brightness transition between the lights and the changes of wind volume as a metaphor of 'airflow of respiration' to present IBI feedback, which helps users in breathing regulation. We used the quietness of nature soundscape as a metaphor of 'peace of mind' to represent HRV data, which indicate the results of relaxation training. This study served as a proof of concept. The qualitative results showed that the mapping design with natural coupling made the represented IBI and HRV data easily be understood and the breathing regulation intuitive and even spontaneous.

We see this study reside in the intersection of biofeedback engineering and HCI design. The design knowledge of 'natural coupling' has been applied to the interface design for biofeedback system. This work may attract more attention to the HCI design for everyday biofeedback system, creating a meaningful presentation mapping between bio-data and external audio-visual displays. Here, we summarize our design processes as a reference that can be easier for other designers to understand and use. Firstly, we suggest understanding the physiological and health-related meaning of the biofeedback data. Take this design as an example, the fluctuations of IBI data indicate breathing movements, and a short-term improved HRV suggests a good result of breathing regulation. The biofeedback displays should not only indicate the value of bio-data but also supply their meanings. Secondly, we suggest addressing dynamic expressions (e.g., using a metaphor) of the interface to simulate or mirror the represented physiological process and further refining expressive parameters for natural coupling, such as the distribution of brightness or the quietness of nature soundscape. Thirdly, the expressive parameters can be further decomposed into some basic parameters, such as acoustic parameters of a sound generator, and light parameters of the lighting controller, to couple with the data.

C. MULTIPLE MODALITIES ENHANCE INFORMATION PERCEPTION

Many researchers suggest that a multimodal display may reduce the cognitive workload and enhance the information perception in a learning process due to the distribution of information processing [32]. For instance, in a complex task, different information can be presented in visual and audio channels. However, in the relaxation training, the self-regulation task (e.g., the deep breathing in this study) and the biofeedback data (IBI and HRV) are very simple. Hence, in the design of *REShance*, the data are presented in both lighting and audio interfaces. The responses from the participants reveal that presenting data in both visual and audio modalities could complement each other. Like one participant stated, she started the breathing regulation by following the lighting feedback and closed the eyes to relax when the lights turned to blue-green. When the nature soundscape turned

noisy, she would open the eyes and follow the lighting feedback again.

D. DESIGNING THE SENSORY STIMULUS FOR RELAXATION

The interactive media used in a user interface can be a potential sensory stimulus influencing user experience. The external signals from the interface might be a booster for relaxation but also might induce new anxiety we expect least. We suggest carefully selecting and modulating the media for a relaxing experience. In our design, the cool-toned light was selected due to its ability to reduce arousals [36] and create a feeling of calmness. The color is modulated by the parameter of saturation instead of the hue, in which way the light can be perceived as a consistent cool-toned color.

Instead of transforming biofeedback data into an audio tone or a melody, we harnessed some well-proven nature sounds to shape a natural acoustic environment as a positive stimulus for relaxation. According to the [41] and [42], we selected five types of birdsong and the murmur of a brook because they can comfort an individual's mind. We applied a perceptual modal of nature soundscape to modulate the nature sounds for a calm experience. Besides, many interactive media can be used in biofeedback interface to shape a comfortable and relaxing experience through the vision, hearing, smell and touch, such as a musical interface or a shape-changing interface for 'massage-style' haptic feedback.

VIII. CONCLUSION

In this paper, we have presented a room-scale audio-visual HRV biofeedback for immersive relaxation training. The *REShance* system presents IBI and HRV data with the ambient lights and a nature soundscape in the room. The experiment has compared the participants' physiological measures and self-report data under three stages: resting baseline, stressful task, and biofeedback-assisted relaxation. The quantitative results suggest that the *REShance* system could efficiently support relaxation training by reducing the arousal level, slowing breath, and enhancing heart rate variability. The interview results reveal that the ambience created by the coloured lights and nature sounds could provide an immersive and engaging user experience. This study shows the potential of ambient medium (light and nature sounds) not only for relaxation training but also for informing the users and promote their self-regulation, e.g., deep breathing. In this light, the findings of this study might be a starting point for further research on ambient biofeedback and a physiologically driven smart home for better health and wellbeing.

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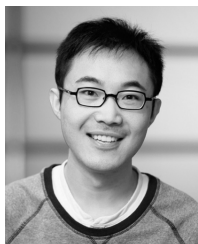
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