Designing Biofeedback for Managing Stress

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PROEFSCHRIFT

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Summary

Mainly provoked by increasing stress-related health problems and driven by recent technological advances in human-computer interaction (HCI), the ubiquitous physiologically-relevant information will potentially transform the role of biofeedback from clinical treatment to a readily available tool for personal stress management. The primary motivation for this thesis is to bring biofeedback techniques closer to everyday use so that the average people can harness it more intuitively, effortlessly and comfortably.

The first part of the thesis aims to understand the current status of biofeedback technology in the context of stress management. We first decompose a biofeedback-assisted self-regulation process from the perspective of an information pipeline. Then we present an overview towards state of the art relevant to the biofeedback techniques for stress management and relaxation training. A systematic literature review is carried out to classify biofeedback systems for stress management, regarding bio-sensing technique, bio-data processing approach, biofeedback protocol, feedback modality, and evaluation approach. This systematic review helps us to identify the challenges and opportunities for biofeedback design.

In the second part of this thesis, we present four novel biofeedback interfaces that are developed with various HCI technologies, such as sonification, metaphorical visualization, shape-changing displays, and haptic interfaces. The 'presentation mapping' in these biofeedback displays embodies a similar design rationale around the idea of 'natural coupling'. The user studies provide sufficient confirmation of the design rationales presented. The natural coupling in presentation mapping may help users associate the interface expressions with their physiological activities and specific meanings relevant to life and health. These associations make the biofeedback representations meaningful and further facilitate the users to understand and leverage the biofeedback information intuitively in their self-regulation and self-reflection.

In chapter 3, we apply the idea of nature coupling to the design of an audio interface for heart rate variability (HRV) biofeedback. The heart rate variability is presented by the changing rhythm of short melodies. In this design, the timing variations of heart rate are directly mapped to the rhythmic variations in MIDI notes. In chapter 4, we present StressTree and HeartBloom, two metaphorical visualizations of HRV data. We introduce the images of tree and flower as visual metaphors in the visualization of HRV data. The traditional IBI tachogram and HRV Poincaré plots are transformed into a common flower or tree image that can be understood intuitively. Besides visualizing the IBI dataset, the appearance of the flower-shape

or tree-shape visualization also represents a health-related physiological meaning semantically. In chapter 5, we present LivingSurface, an interactive wall-like surface as a shape-changing display of biofeedback. LivingSurface aims at using the qualities of a physical change to enhance the interaction with digital biofeedback information. The expressivity of LivingSurface is explored to embody the interface with a sense of life. In chapter 6, we present Breathe with Touch, a tactile interface that simulates human breathing movements through the inflation and deflation of an airbag. The natural coupling between the user's breathing behaviour and the interface's action is designed to facilitate an automatic breathing regulation.

In the third part, we explore using ambient media for biofeedback display. The initial intention is simple: to turn the biofeedback system into 'invisible background', where the users can perceive their internal physiological states from an environment without computer screens. We utilize nature sounds and ambient lights for an engaging and comforting biofeedback interaction. In chapter 7 and 8, we design an auditory display with nature sounds. We conduct an experimental study to test the modulation of various nature sounds for calm information display. The study concludes with a simplified three-layer structure and a nature soundscape model, which is used in the design of BioSoundscape in chapter 8. BioSoundscape harnesses nature sounds to create a 'calm' nature soundscape that responds to the user's physiological activities. It can not only serve as an ambient biofeedback display but also be integrated into an indoor acoustic environment as a natural augment. In chapter 9, we present DeLight, an ambient lighting biofeedback system. The intent of DeLight is not only to present biofeedback data but also offer a comforting environmental stimulus for relaxation training. In chapter 10, we integrate the BioSoundscape and DeLight together into a room-scale audio-visual biofeedback system: RESonance. It offers a lightweight solution for immersive biofeedback training. In chapter 11, the developed RESonance biofeedback system was applied in a multi-session biofeedback training with five PhD students and five young soccer players. We evaluate the effectiveness of biofeedback in skill-learning for stress coping, and also investigate the users' learning curve with biofeedback.

In the last part of the thesis, we formulate our answers to the research questions and conclude our contributions to the research and design biofeedback for stress management. We indicate four future research directions in everyday biofeedback: Inherent Biofeedback, Adaptive Biofeedback, Casual Biofeedback and Peripheral Biofeedback. In conclusion, this thesis presents a design-driven exploration of biofeedback applications for managing stress. The design explorations cover a broad design space including data sonification, metaphorical visualization, shape-changing displays, tangible interactions, and ambient displays. In these explorations, the designs themselves become a resource for new knowledge through empirical research surrounding the evaluation of these works. We hope this work could be a starting point for initiating a new field of 'Everyday Biofeedback'.

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PART I

Mirrors are among of the most common items in our everyday life. They allow us to see our looks, postures, movements, and facial expressions. Moreover, mirrors are also a powerful learning tool. The best example might be that big mirrors in a dancing room help students to correct postures. Imagine now that you have a special ‘bio-mirror’ that can reflect your internal states and show what is happening inside your body. Would you be willing to use it in your everyday life? You may look through this bio-mirror to know yourself better and use it to better manage your physiology, stress, and health. This bio-mirror has a technical name: biofeedback. This thesis centers around biofeedback in the context of stress management and relaxation training. In chapter 1, we introduce the motivation of the research, the working of biofeedback, and the challenges in biofeedback design. In chapter 2, we summarize the current state of biofeedback research for stress management and look for design opportunities regarding human-computer interaction.

1
Introduction

1.1 Background

1.1.1 Chronic stress

According to the survey 'Stress in America' conducted by *American Psychological Association* (2015), an increasing number of people are suffering from chronic stress in their everyday life. The external adverse stressors constantly challenge the dynamic homeostasis of our body (Chrousos 2009). Stress is a biological and psychological response. Stress responses occur when a situation is perceived to be challenging or threatening (e.g., meeting a work deadline or facing a speeding car). The stress responses are mediated by our 'stress system,' which involves the amygdala and hypothalamus located in the central nervous system, autonomic nervous system, glands, and organs. When our brain perceives a situation as a stressor, it sends a distress signal to the hypothalamus, which then activates the sympathetic branch of the autonomic nervous system (ANS) sending signals to the adrenal glands (Porges 1995). The hormone epinephrine is pumped into the bloodstream and acts on the target organs, speeding up the heartbeat and breathing, stiffening the muscles and causing sweating. The combination of these reactions is known as the 'fight-or-flight' response which enables us to react quickly to life-threatening situations and helps us fight the threat off or flee to safety. The acute stress is transient, beneficial and even vital in most cases. When stressful situations pass, the parasympathetic branch of ANS will be activated, acting as a 'brake' to dampen the stress responses and help to re-establish the homeostasis.

Unfortunately, this brake might fail to operate when our body overreacts to some chronic stressors, such as long-term work pressure. When the brain continuously perceives the situation as stressful, the always-on 'fight-or-flight' responses may put the ANS off balance and further deteriorate the responsiveness of our stress system. The cumulative effects of chronic stress often degrade our performance in work (Scott, Hwang, and Rogers 2006). Physiologically, the long-term activation of adrenal glands can release excess cortisol (stress hormone) which may disrupt various bodily processes and disturb the homeostasis (Chrousos 2009). Chronically elevated cortisol level puts high-stress individuals at an increased risk of numerous health problems, including anxiety, depression (Burke et al. 2005), immune dysregulation (Padgett and Glaser 2003), heart disease, hypertension (Esler and Kaye 2000) and diabetes (Lloyd, Smith, and Weinger 2005).

Keeping stress in an 'optimal zone' facilitates both work performance and overall health. An optimal responsiveness of the body's stress system is also essential for proper emotion regulations in social interactions and a sense of well-being. Therefore, various stress-coping techniques have been developed and used to help people maintain the homeostasis and the autonomic balance. For instance, listening to relaxing music can decrease cortisol level and help stress recovery (Khalfa et al. 2003). The research by Alvarsson et al. (2010) suggests that the stress recovery will be faster and more complete when the users are exposed to colour and sound stimuli from natural environments. Tang et al. (2009) documented that a short-term meditation practice may improve the balance of ANS. The mindfulness practices show several positive benefits including decreased anxiety and increased focus and mood (Smith 2014). As suggested by Streeter et al. (2012), yoga practices can also stimulate an underactive parasympathetic nervous system and help to correct the imbalance of the ANS.

1.1.2 Biofeedback in stress management and relaxation training

Biofeedback (Brown 1977) is a special mind-body technique that brings unconscious physiological processes under conscious control. Biofeedback instruments use various bio-sensors to measure bio-signals from a user's body and provide specific physiological information (e.g., arousal activities, heart rate variability, or brain waves) back to the user with an external visual or auditory display. Biofeedback is often regarded as a special 'Bio-Mirror' that enables people to see their bodily processes and internal states. Also, it has been well proven as an effective tool to improve self-awareness, enhance self-regulation, and facilitate self-reflection for improving health.

In clinical applications, biofeedback techniques often serve as a special intervention or an addition to cognitive and behavioural therapy (Hauri 1975). For instance, they are often used to treat anxiety disorders (Reiner 2008) and reduce psychological stress during the early postpartum period (Kudo et al. 2014). In stress management and relaxation training, biofeedback instruments allow the users to observe negative impacts of stress on their physiology and further to manage stress responses and achieve a psychophysiological relaxation. As personal biofeedback products emerge recently, biofeedback training is increasingly used by many high-stress groups for stress management, including medical staff (Smith 2014; Cutshall et al. 2011), musicians (Wells et al. 2012), students (Ratanasiripong et al. 2015; Henriques et al. 2011) and athletes (Paul & Garg 2012; Pusenjak et al. 2015).

1.2 Biofeedback Interaction Framework

In this section, we propose a biofeedback interaction framework to better describe the working of biofeedback from the HCI perspective. Biofeedback can facilitate behavior conditioning to achieve a targeted internal state and skill-learning to enhance self-regulation (Nishimura et al. 2007). During these processes, biofeedback instruments rapidly and accurately 'feed back' information to the users. The effectiveness of biofeedback is related to how the users perceive, understand, and use the feedback in their self-regulation or behavior conditioning. As shown in Fig 1.1, biofeedback is a closed-loop system in which the measured bio-signals are translated into external audio-visual signals that are perceivable by one or more of the human senses. The working of biofeedback can be described as a sequence of data transformations that go through several stages until the external signal is produced, presented and perceived. Several interaction frameworks and models have been proposed to describe the HCI and information display, such as visualization frameworks by Ed Huai-Hsin Chi & Riedl (1998) and Jansen & Dragicevic (2013), a sonification framework by Hermann & Hunt (2005), and a tangible interaction model by Ishii (2008). Specifically, Rovers et al. (2009) proposed a biofeedback model for designing a biofeedback game. Al Osman et al. (2014) proposed a reference model for ubiquitous biofeedback. It offers a prospect for biofeedback design beyond the clinical context.

Fig 1.1 Biofeedback is a closed-loop system translating bio-signals into audio-visual displays. Image by Xinwei Wang

As shown in Fig 1.2, we synthesize the interaction model proposed by Jansen & Dragicevic (2013) and biofeedback learning theories (Norris 1986; Deborah L. Butler & Philip H. Winne 1995) into a new biofeedback interaction framework. It describes a typical information pipeline in most biofeedback systems. The framework consists of four main stages: biofeedback computing, biofeedback representation, cognitive processing, and self-learning. The biofeedback loop starts from a user's body, which is connected to various biosensors. The measured bio-signals are digitized and transmitted from the bio-sensing front-end to the biofeedback software. In the first stage of biofeedback computing, the bio-data are further processed and analyzed to derive the metrics of specific physiological activities. This process usually combines different approaches to biomedical signal processing, such as filtering, frequency analysis, and feature extraction.

In the second stage, the ready-processed data are prepared for biofeedback display. In the audio-visual mapping, the data are mapped to some basic visual or audio variables, such as height, color, pitch or volume. For instance, in a computer-based visualization system, those visual variables typically correspond to graphical attributes. Next, in the presentation mapping, the basic variables of newly-loaded data are further transformed into a fully-specified audio-visual representation that can be displayed. This transformation usually involves several operations including scaling to amplify the encoded audio-visual variables, assigning audio-visual variables in a way that can facilitate the reading of representations, and adding extra audio-visual variables of the context to facilitate the understanding of the representations. Through different interactive media, these representations are finally displayed to the user.

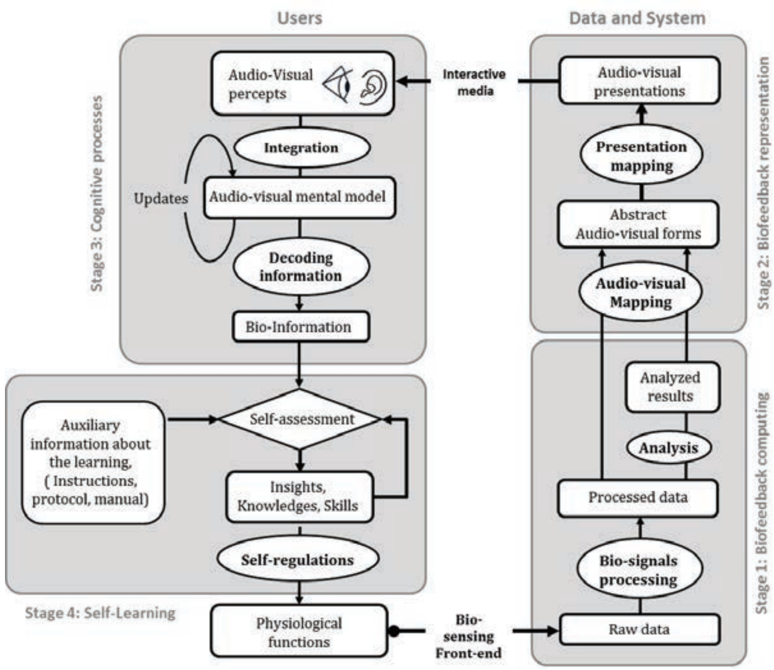

Fig 1.2
The Biofeedback Interaction Framework describing the information pipeline in most biofeedback systems

In the third stage, the biofeedback displays are perceived and interpreted. The user receives the audio-visual representations as a percept. The new percepts are combined with previous percepts to update the mental model of the audio-visual presentation. Decoding information refers to a process of extracting and understanding the data values from the audio-visual mental model. The difficulty of this decoding process is determined by the complexity, recognizability, and readability of the representations. It may also depend on the user's literacy and the degree of training. Cognitive processes are complex and differ across users according to Zhicheng Liu & Stasko (2010). Therefore, this framework does not try to elaborate on those cognitive processes.

In the last stage of self-learning, besides the extracted data value, the user also needs to be informed about how physiological activities are represented in the feedback and what the goal of learning is. The learning-related auxiliary information is essential for the user to improve the self-regulation skills. Typically, a biofeedback training protocol is first designed based on different user groups, biofeedback displays and learning purposes. And then the corresponding manuals and instructions can be further specified (Lehrer et al. 2000). Constantly comparing the feedback (about the physiological processes/states being regulated consciously) to the learning goal (the targeted physiological state) in self-assessment generates conditional insights which can be used to adjust further regulations. The mental or behavioral self-regulations, such as breathing regulation, positive imaginary, and progressive relaxation, directly or indirectly act on the user's physiology that is being measured and the collected bio-signals are fed into the biofeedback loop again. Through trial and error, the user may acquire and improve the skills for self-regulation and find out his/her specifically effective way to achieve the goal.

1.3 Challenges and Opportunities

Despite an increasing body of evidence suggesting that biofeedback techniques can contribute to self-regulation of stress, there is still some distance left before biofeedback become a practical tool for stress management in daily life. In this thesis, we aim to address the following two aspects of biofeedback applications.

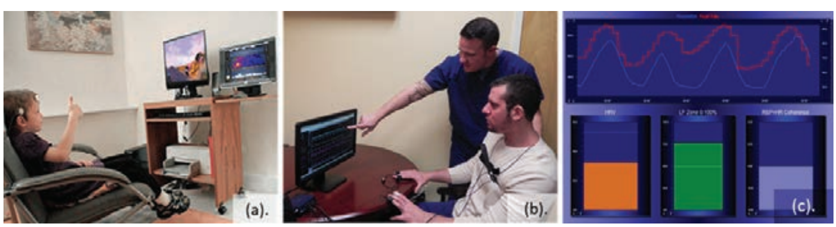

Fig 1.3 (a) A young patient performing biofeedback training in the therapy room (b) a therapist explaining the meaning of the graphics to his patient (c) a typical graphic interface of the professional biofeedback system, *BioTrace*[1], *MindMedia,* the Netherlands

1. BioTrace+, MindMedia: https://www.mindmedia.com/products/biotrace-software, retrieved:13-11-2017.

1.3.1 Self-use of biofeedback is not supported well by existing applications

Biofeedback techniques have been used in clinical applications for more than 40 years. Due to high hardware costs and operation difficulties, biofeedback trainings are usually performed in a therapy room with the assistance of a well-trained therapist see Fig 1.3(a-b). As shown in Fig 1.3(c), the traditional biofeedback displays tend to follow a medical or technical style that is designed for therapists and clinical staff. According to the biofeedback interaction framework, in the stage of biofeedback representation, these traditional interfaces mainly focus on the audio-visual mapping where the data are only transformed into an abstract audio-visual representation, such as bars, graphs, audio tones or indicator light. The presentation mapping has rarely been addressed. Hence the reading and understanding of these representations are not an easy task for the professionals, not to mention the average users. The therapists need to be trained as an expert to explain the meaning of the representations and instruct the patients to use the feedback correctly. Many literatures (Smith 2014; Cutshall et al. 2011; Wells et al. 2012; Henriques et al. 2011; Paul & Garg 2012; Pusenjak et al. 2015) show that most of today's biofeedback applications still need the assistance from a therapist and based on a training routine.

The efforts from HCI community are introducing biofeedback techniques from clinical applications to everyday use. Various portable products and mobile applications (e.g., *StressEraser*[2], *emWave*[3], and *InnerBlance*[4]) are available to average people for biofeedback training in everyday life. We see a newly computer-mediated self-use is replacing the traditionally therapist-mediated biofeedback training. In self-use of biofeedback, users have to read and interpret feedback themselves. To facilitate information perception, most of the early-stage personal biofeedback products employ a multi-modal display which distributes the information processing into different sensory modalities. The provision of biofeedback information in both audio and visual modalities can improve the usability of the interface (Burke et al. 2006). For instance, the biofeedback data are often represented by on-screen graphs with an audio tone (Moore 2006). In another example, *emWave* uses an indicator light coupled with an audio cue to show the coherence value between respiration and heart rhythm (Whited et al. 2014).

More recently, rather than pursuing all-embracing accessibility like those commercial biofeedback products, some researchers and designers focus on a scenario-based biofeedback design, in which the HCI-designs are specialized for different purposes, targeted users, and the context of use. In their designs, the biofeedback displays were developed into new form-giving and deployed with new interactive-media. For instance, in driving or working situations, biofeedback displays are often designed for the periphery of attention. Respiration or heart rate data can be represented by a piece of music during a visually-demanding task (Bhandari et al. 2015; Yokoyama et al. 2002). A driver's stress level can also be

2. StressEraser http://www.stresseraser.nu/, retrieved:13-11-2017.

3. emWave, HeartMath, https://store.heartmath.com/emwave2, retrieved:13-11-2017.

4. InnerBlance, https://store.heartmath.com/innerbalance, retrieved:13-11-2017.

represented by a shape-changing gadget worn on the wrist (MacLean et al. 2013). Under a working condition, an office worker's breath rate can be displayed on the operation system tray of a personal computer (Moraveji et al. 2012) or by a semi-translucent grey bar stretching across PC screen (Moraveji et al. 2011). In home environments, biofeedback can be displayed by ambient light (Lee & Yoo 2008), as a Chinese ink painting projected on the wall (Zhu et al. 2013) or with a shape-changing interface integrated into furniture in the living room as part of the interior design (Feijs & Delbressine 2017).

In recent biofeedback products, the usability and accessibility have been significantly improved, which led to better acceptance and satisfaction for average users. In those new biofeedback systems, by addressing the presentation mapping, biofeedback displays started to take various forms including music, soundscape, animation, game, light, and physical shape changes. In our view, the link between biofeedback data and interface expressions has not yet been addressed well. Without the therapist's instructions and explanations, intuitive perception of biofeedback data and a correct understanding of their physiological meanings become especially important. Besides creating new form-giving, the presentation mapping can also be addressed to give an interface a proper expression that can be naturally associated with a human physiological process or common cognitive knowledge. The newly created associations may facilitate the reading, decoding, and understanding of a biofeedback representation. Hence, we argue that the presentation mapping should be addressed not only for form-giving but also for sense-making.

1.3.2 An engaging biofeedback training is difficult to achieve in a simple way

For stress management, biofeedback systems are used as a learning tool for improving self-regulation skills, such as deep breathing (Sonne & Jensen 2016), arousal modulation (Yokoyama et al. 2002), muscle relaxation (Rokicki et al. 1997) and even control of the brain waves (Kosunen et al. 2016). Besides correctly understanding the feedback, the user's engagement in a biofeedback training is a key to deeper and more sustained practice. In clinical applications, user engagement and experience are seldom considered. The traditional graphic and numeric displays seem less engaging for everyday use. Therefore, in recent years, many efforts from HCI have been made to enhance user experience with biofeedback in different aspects, such as playfulness (Sonne & Jensen 2016; van Rooij et al. 2016), aesthetics (Šimbelis et al. 2014; Muller et al. 2006) and immersiveness (Roo et al. 2017).

For increasing playfulness, a variety of biofeedback games have been created. Sonne & Jensen (2016) designed a breath-controlled biofeedback game for helping the children with ADHD control their stress level. The authors applied gamification to the biofeedback system for sustaining users' attention and engagement with breathing training. DEEP (van Rooij et al. 2016) provides breathing biofeedback through a VR game which situates the player in a virtual underwater environment. To shape an aesthetic experience, many biofeedback artworks and installations have been created for somaesthetics (Shusterman 1997) or artistic explorations. Metaphone (Šimbelis et al. 2014) facilitates relaxation practices by engaging the users in a biofeedback installation which embraces artistic visualization and machine aesthetics. The artist George Khut (2016) has created a series of digital biofeedback artworks which address the audience's experience with aesthetic bio-data visualizations and sonifications. Besides playfulness and artistic attractions, a meditative or immersive experience may also enhance user engagement by facilitating a state of mindfulness. As such, the immersiveness was usually emphasized in the design of relaxation systems. For instance, ExoBuilding harnesses lights, sounds and the spatial changes of an architectural prototype to immerse its inhabitant in relaxation training (Adelbach et al. 2012). InnerGarden utilizes a tangible artifact, spatial Augmented Reality, and a VR headset to provide an engaging mindfulness training (Roo et al. 2017).

Typically, such a biofeedback game, installation, architecture or VR application has a high adaption threshold and high deployment cost. It is relatively difficult to deploy them in home or working environment due to their specified requirements on space arrangements, new hardware, or operating configurations. Thereby, the majority of these experience-oriented biofeedback systems are still restricted to laboratory or exhibition settings. In our view, the ambient media in everyday environment offers a lightweight solution to strike a balance between engagement and ease of deployment. In future smart-home, everyday objects are increasingly internet-connected and may serve as an interactive media for biofeedback, creating a physiologically-responsive, immersive environment for personal stress management and relaxation training. Hence, we see the opportunities of ambient media to be harnessed not only for conveying biofeedback information, but also for enhancing user experience and engagement.

1.4 Objectives

In this thesis, we intend to face these challenges through the exploration of human-computer interactions for biofeedback. The primary motivation is to further bring biofeedback technique closer to everyday use so that the average people can harness it more intuitively, effortlessly and comfortably. As shown in Fig 1.4, we pinpoint our research on the two parts in the proposed biofeedback interaction framework: **Presentation mapping** and **Interactive media**. We start with design explorations on presentation mapping to associate the interface expressions with specific physiological activities or semantics of life and health. Secondly, we explore ambient biofeedback with interactive media of spatial lights and nature sounds for improving the engagement and comfort of biofeedback-assisted relaxation training.

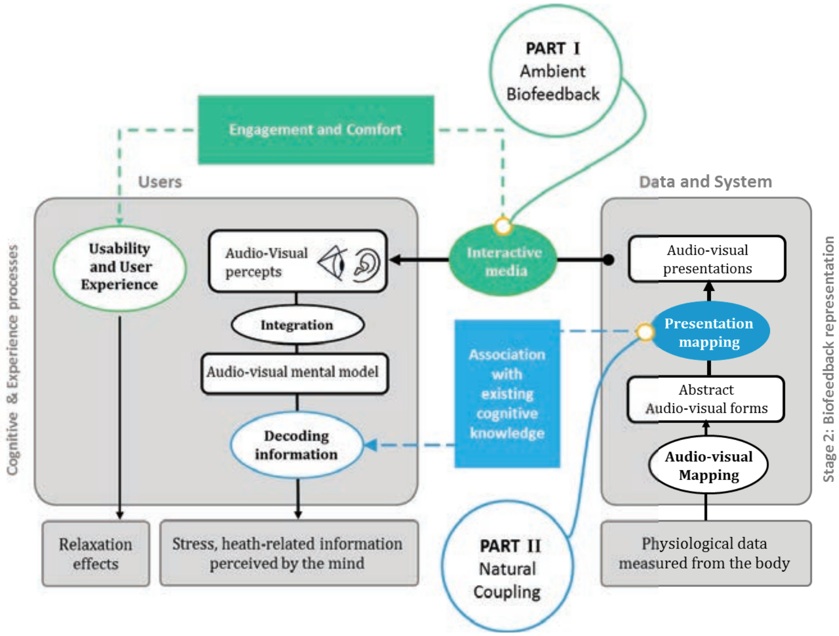

Fig 1.4
The main explorations in the thesis focus on two parts: Presentation Mapping and Interactive Media

1.5 Thesis Outline

This thesis is divided into four parts as follows. We formulate the objectives of the research and the research questions to be answered. Fig 1.5 shows the research roadmap and an overview of all chapters. These chapters follow a chronology.

- **PART I:** Introduction and literature review
- **PART II:** Natural-coupling for biofeedback interaction
- **PART III:** Ambient biofeedback interaction
- **PART IV:** Discussion and conclusion

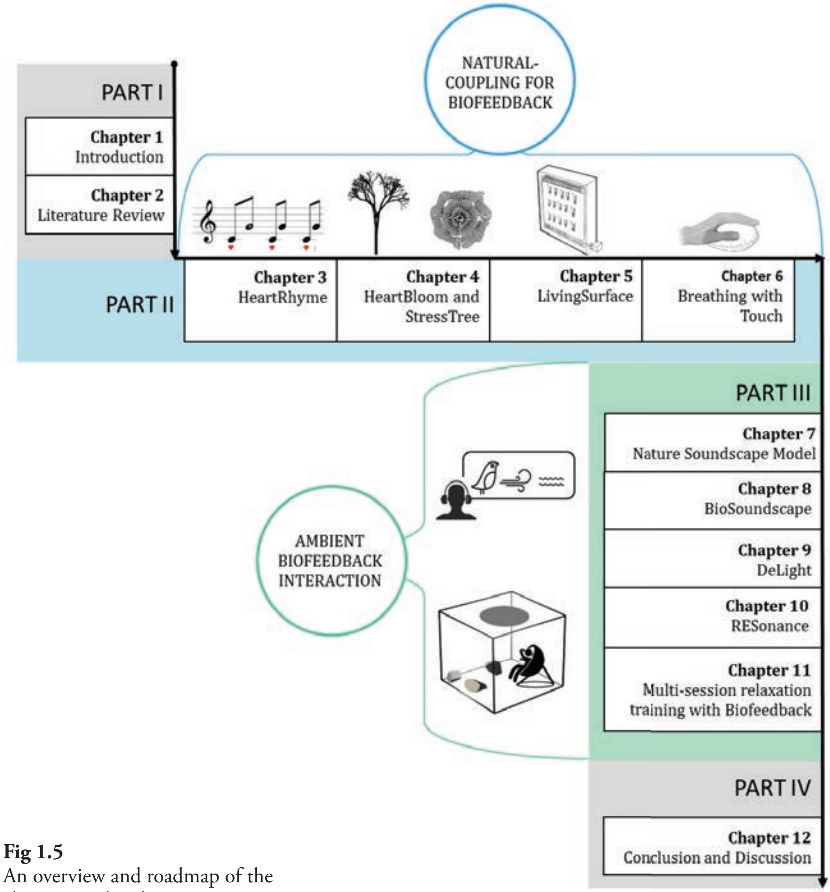

Fig 1.5
An overview and roadmap of the chapters in this thesis

1.5.1 Part I: Introduction and literature research

The first part of the thesis aims to understand the current status of biofeedback techniques for personal stress management. We first decompose a biofeedback-assisted learning process from the perspective of information pipeline. Then we present an overview towards state of the art relevant to the biofeedback applications for stress management and relaxation training. A systematic literature review is carried out to 1) classify biofeedback systems for stress management, regarding bio-sensing technique, bio-data processing approach, biofeedback protocol, and feedback modality; 2) inventory the evaluation approaches for biofeedback effectiveness; and 3) identify the challenges and opportunities for biofeedback design.

1.5.2 Part II: Natural-Coupling for biofeedback interaction

Biofeedback instruments are a particular type of interactive products, whose feedback inform users about their self-regulation by showing that how physiology is responding, indicating the training progress, and confirming the results. A user's interactions with biofeedback system constitute a self-learning process, where the feedback information serves as an essential 'learning material' for acquiring self-regulation skills. Regarding interaction and feedback design, Djajadiningrat et al. (2002) suggested that the appearance of a product may communicate meanings semantically. Wensveen et al. (2004) proposed the concept of 'inherent feedback' for tangible interaction. They suggested strengthening the coupling between the user's action and the product's feedback ('reaction') for creating meanings in user-system interaction. As inspired by their work, we think that the mappings from physiological data to the 'appearance' and 'actions' of a biofeedback interface should also be inherently linked and naturally associated with each other. In the second part, we explore the idea of 'natural coupling' in the design of 'presentation mapping' for biofeedback interfaces. We assume that the natural coupling may help users associate the interface expressions with their physiological activities and specific meanings relevant to life and health. These associations may further facilitate the users to read, understand and leverage the feedback information more effortlessly and intuitively in their self-regulation. We formulate the research question for Part II as follows:

Research question 1. *How to design 'Natural Coupling' for biofeedback interaction that facilitates the user's understanding of physiological data?*

1.5.3 Part III: Ambient biofeedback interaction

Since Mark Weiser (1991) coined the term Ubiquitous Computing, the idea of a peripheral and environmentally integrated way of displaying information has been appealing to many researchers and designers in HCI. Ubiquitous computing (Weiser 1999) envisions a new paradigm of HCI which attempts to push computers into an 'invisible background'. Mark Weiser & John Seely Brown (1997) further formulated the Calm Technology, which suggests that the information can be conveyed via calm changes in the environment. Inspired by the vision of Ubiquitous Computing and Calm Technology, in the third part, we intend to explore a certain form of ambient biofeedback for an engaging and comforting biofeedback-assisted relaxation training.

Research question 2. *How to design ambient biofeedback for an engaging and comforting biofeedback training?*

1.5.4 Part IV: Discussion and conclusion

In the last part, we present a general discussion of the findings and the limitations in our work. We formulate our answers to the research questions and conclude our contributions. We indicate four future directions of biofeedback research for personal stress management: Inherent Biofeedback, Adaptive Biofeedback, Casual Biofeedback and Peripheral Biofeedback. For each direction, we provide a summary of implications extracted from the findings of our design cases presented in Part II and Part III.

2
Systematic Review

2.1 Background

Compared to the earliest applications of biofeedback at the beginning of the 1960s, the embodiment and the modality of biofeedback have been broadened beyond traditional desktop settings. Advanced biosensors make the data collection more convenient and unobtrusive. Physiological computing can be completed on different platforms such as laptops, mobile phones, and wearable devices. As such, biofeedback systems are becoming increasingly portable and affordable, and various physiological data are readily available in our everyday life. The innovations of HCI significantly improve the acceptance, accessibility, usability and user experience of biofeedback systems. With new interactive media, the user interactions with a biofeedback system are no longer restricted to on-screen GUIs but become increasingly diversified for different contexts, such as through tangible interaction (Ishii 2008), peripheral interaction (Bakker et al. 2015), shape-changing interfaces (Rasmussen et al. 2012), ambient display (Ishii et al. 1998), and musical interfaces (Gaye et al. 2003). Nowadays, biofeedback techniques are more than a treatment for medical disorders but become a learning tool for average people to improve self-regulation skills and cope with stress in daily life.

It is well-accepted that biofeedback, provided by a professional display and assisted with a therapist, can effectively treat various stress-related or stress-induced disorders. Biofeedback application has been widely reviewed in medical fields regarding its evidence, approaches and protocols. Some literature reviews summarize and report the principles and practices of biofeedback in clinical applications (Blanchard et al. 1974; Basmajian 1981). Some provide in-depth overviews of biofeedback techniques for different medical treatments, including headache disorders (Nestoriuc et al. 2008), anxiety disorders (Moore 2000), hypertension (Greenhalgh et al. 2010), functional anorectal disorders (Palsson

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This chapter is largely based on

Yu, B., Funk, M., Feijs, L., & Hu, J. (Under review). Biofeedback Learning for Stress Management: A Systematic Review. *Journal of Frontiers in ICT* et al. 2004), chronic pain (Turk et al. 1979), stroke rehabilitation (Glanz et al. 1997). Yet no review has evaluated and discussed the biofeedback applications for non-therapeutic stress management, especially regarding the human-information interaction. In this chapter, we present a systematic review that summarizes the last 25 years of research on biofeedback applications, regarding bio-sensing technique, bio-data processing, feedback display, usage scenarios, and evaluation approaches. Based on this review, we hope to identify the research gaps that have not yet been fully explored and the design opportunities in biofeedback design. The systematic review mainly answers the following four questions:

- What types of biofeedback techniques are commonly used for non-therapeutic stress management?
- How is the physiological information presented to the users?
- How is the biofeedback system used for personal stress management?
- How do the researchers or designers evaluate the effectiveness of biofeedback?

2.2 Methodology

2.2.1 Data sources and search strategies

We searched for relevant studies in the following electronic databases: PubMed, IEEE Xplore, ACM, and Scopus. To seek out related articles, we selected papers addressing two aspects: 'Biofeedback' and 'Stress Management'. The following search strategy was applied in PubMed database. MeSh (Medical Subject Heading) terms (the bold terms below) and their synonyms and spelling variations were used in several combinations and modified for the other databases.

#1 Biofeedback (biofeedback OR bio-feedback OR "augmented feedback" OR "sensory feedback" OR "sensory augmentation" OR "proprioceptive feedback" OR "auditory feedback" OR "audio feed-back" OR audio-feedback OR "visual feedback" OR "audiovisual feedback" OR "audio-visual feedback" OR "somatosensory feedback" OR "tactile feedback" OR "vibrotactile feedback" OR "vibratory feedback" OR "multimodal feedback")

#2 Stress ("stress reduction" OR "stress management" OR "stress coping" OR "stress relief" OR "stress intervention" OR distress OR anxiety OR meditation OR relaxation)

#3 (1 AND 2)

2.2.2 Selection criteria

All available studies were considered as they applied biofeedback for stress management in general population for non-therapeutic purposes. Biofeedback was defined as measuring a user's physiological activities and providing the user with concurrent feedback information on the measured activities through the human senses. Stress management stands for any activity that helps to control, regulate and reduce the stress responses which are not caused by diseases or trauma. Articles published from 1990 to 2016 were reviewed.

The following exclusion criteria were applied to narrow down the set of relevant studies further. Firstly, regarding the applications of biofeedback, this review focuses on the biofeedback techniques for casual users in everyday use. Therefore, the articles about the applications for therapeutic purposes or as a treatment for severe stress disorders were excluded. For instance, we excluded the reports on using biofeedback for treating the stress problems that are caused by trauma (PTSD) (Lande et al. 2010), physical or mental illnesses (Reiner 2008). Secondly, regarding the evaluation of the outcomes, the studies were considered if they used at least one objective measure of biofeedback effect on stress management. The studies that only describe the development of biofeedback system were excluded. Thirdly, the articles were excluded if they were too general or too theoretical; for example, the articles that only presented a general biofeedback diagram or introduced a design framework were excluded, e.g., (Matuszek & Rycraft 2003). Also, the articles were excluded if they were review articles, non-English publications, or 'grey' literature, such as abstracts, tech reports, dissertations and theses.

2.2.3 Selection procedures

The search was performed on January 8th, 2017. Two independent reviewers screened the titles and abstracts of the results obtained by the database search. After title-abstract screening and duplicates check, we created an initial pool of articles. In the second filtering, these full-text articles were then analyzed and evaluated again by the reviewers independently. In the case of discrepancies between the two reviewers, a third reviewer decided whether the article should be included. During this process, the related studies cited in the articles were progressively included into our final database.

2.3 Results

2.3.1 Search results

An overview of the results in different stages of the article selection process is visualized in Fig 2.1. The initial literature search yielded a total of 2540 articles relevant to this review. After title and abstract screening, winnowing out duplicates and off-topic studies, 102 studies remained. The full papers of the remaining 102 studies were assessed to select those primary studies in biofeedback that directly related to stress management.

Based on the stated exclusion criteria, 45 of the 102 publications were eligible for the current review. An additional article was retrieved from the reference and added to the database. The common reasons for exclusion included the lack of evaluation, the absence of system description or for the treatment of stress caused by diseases or trauma. In other cases, when authors published several studies on the same research initiative, we only included their most recent research that satisfied the inclusion criteria. Each study in the final selection (n=46) was reviewed to extract the information about biofeedback techniques (e.g., measured bio-signals, biosensors), feedback presentations (e.g., types, contents, modalities, interactive media), stress management approaches, evaluation methods, and experiment design. The results are summarized in Table 2.1.

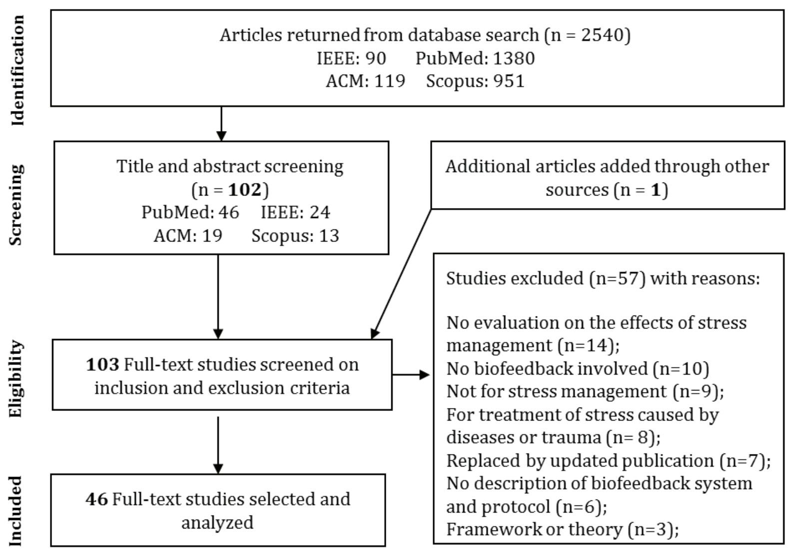

Fig 2.1 Prisma (Moher et al. 2009) flowchart of the results from the literature search

Table 2.1. Summary of the paper lists and features

Studies	Biofeedback technique			Presentation		Involved stress alleviation		Evaluation	
References	Mode	Bio-data	Content	Form-giving	Media	Context	Main instructions	Credits	Experiment design
(Larkin et al. 1992)	HR	ECG	HR level,	Background color of the screen	PC-based	Under stressful game	The subject is instructed to improve the performance of video game and lower the HR	HR, Performance scores	Between-Subjects (n=12); BFB vs. Blank control; Repeated trials (5 Sess, 6 min/Sess)
(Yokoyama et al. 2002)	HR	ECG	IBI data	Pitch and note intervals of MIDI data	Ambient Sound system	Under a work task	Being awareness of heart rate level and learn to keep it low.	HRV Self-reports, Performance	Within-subjects (n=22); BFB vs. Blank control; One-shot trials (3min/Sess);
(Goodie & Larkin 2006)	HR	ECG	HR	Background colors of the screen	PC-based	During video game, arithmetic tasks	Subjects were instructed to reduce HR below the target goal using feedback presented on the monitor.	HR, task performance	Within-subjects (n=14); After BFB no delay vs. short delay vs. long-delay , One-shot trial (2 h/Sess)
(Peira et al. 2014)	HR	ECG	HR	Background color changes on the screen.	PC-based	Under negative pictures stimulus	The subjects were instructed to either "Regulate" or "Monitor" their heart rate during picture presentation.	HR, TAS, STAI, EAQ, ECQ, ERQ,	Within-Subjects (n=22) BFB vs. Blank control; Single-trial (10 min)
(Mccraty et al. 2009)	HRV	BVP	IBI data Cardiac-Coh,	Wave on-screen display	PC-based	Breathing exercise	The subjects learn to achieve heart rhythm coherence by developing a stable, sine-wave-like pattern in the RSA waveform, oscillating at a 0.1 Hz frequency.	Lipid Panel, BP, HRV, Adrenal Index, JAS, BSI, POQA	RCT (n=44 /group), BFB vs. Blank control; Repeated trials (3 months, 1 Sess/day, 15 min/Sess)
(Lemaire et al. 2011)	HRV	BVP	Cardiac-Coh	Light color; Audio cue	Portable device	Breathing exercise	The color of LED light indicates the coherence level as a result of training. The users practice resonant breathing to increase coherence level.	Coherence score, HR, BP, salivary cortisol level.	RCT (n=20/group); BFB vs. Blank control; Repeated trials(30 days, 3 Sess/day, 5 min /Sess)
(Henriques et al. 2011)	HRV	BVP	Cardiac-Coh, IBI data	Coherence Bar Chart (CBC), graphics	PC-based	Breathing exercise	Users attempt to smooth the RSA graph, increase the percentage of time spent in medium and high coherence score.	STAI, MASQ,	Pretest-post-test (n=9); BFB vs. Pre-baseline; Repeated trials (1 month, 5 Sess /wk, 20 min/sessions)
(Paul & Garg 2012)	HRV	BVP	IBI data RSP-R	Graphics	PC-based	Breathing exercise	Detect the resonant frequency when RSA reaches the peak amplitude with biofeedback equipment. The subject was then asked to breathe at his resonant frequency and relax.	STAI, CSES, HRV indices, RES-R,	RCT (n=10 /group), BFB vs. Blank control Repeated trials (10 Sess, 1 Sess/day, 20 min/Sess)
(Purwandini Sutarto et al. 2012)	HRV	BVP	IBI data	Graphics display	PC-based	Breathing exercise	The users aimed to maximize the peak amplitude of RSA through respiration regulation	HRV index, DASS,	RCT (n=18/group); BFB vs. Blank control; Repeated trials (5 Sess, 1 Sess/wk, 30 min/Sess)
(Wells et al. 2012)	HRV	BVP	IBI data	Graphic display	PC-based	Breathing exercise	The subjects were instructed to increase the amplitude of RSA by breathing with the pacer, achieving the best possible feedback graph score while breathing in a free, relaxed way.	STAI, HRV indices	RCT (n=15/group) BFB vs. Blank control; Single trial (30 min),
(Zhu et al. 2012)	HRV	ECG	LF/HF ratio	Audio tone, Visual bar	PC-based	Breathing exercise	Practice the abdominal breathing to improve the value of LF/HF ratio.	LF/HF ratio	Within-subjects (n=3); audio- vs. visual-BFB vs. Blank One-shot trial (15 min/Sess);
(Prinsloo et al. 2013)	HRV	BVP	IBI data	Graphic display	Portable device	After Stressful Stroop task	The subjects are instructed to relax and inhale until the RSA wave reached its peak and exhaled until the wave started to rise again.	RES-R, HR, HRV indices,	RCT (n=9 /group); BFB vs. Blank control; One-shot trial (10 min/Sess)
(De Jonckheere et al. 2014)	HRV	BVP	HR, Cardiac-Coh	Bar chart, Numbers, Animations	Mobile APP	Breathing exercise	Regulate the respiration to increase the cardiac coherence score.	Cardiac Coherence value	Within-subjects (n=19); BFB+guide vs. BFB only; One-shot training (2 min /Sess);

(Whited et al. 2014)	HRV	BVP	HRV power spectrum, Cardiac-Coh,	Graph display	PC-based	Breathing, exercise Positive emotion	Breathe deeply and Recall a positive feeling. The goal is to create a smooth and ordered pattern of RSA waveform and high coherence level.	HRV indices, BSI, PSS,	RCT (n=14/group); BFB vs. Blank control; Repeated trials (5 Sess, 1 Sess/wk, 30 min /Sess)
(Gaggioli et al. 2014)	HRV	ECG	HRV (not specified)	Visual elements in a 3D virtual scene	3D VR Device	Under a stress induction VR game	VR-based scenario simulates the stressful experience; the subjects learn to cope with this induced stress with biofeedback.	PSS, VAS, STAI,	RCT (n=20/ group); BFB vs. Blank control; Repeated trial (10 Sess, 2 Sess/wk 60 min/Sess),
(J. Lee et al. 2015)	HRV	BVP	Cardiac-Coh, IBI data	Coherence Bar Chart (CBC), graphics	PC-based	Breathing exercise	Users attempt to smooth the RSA graph, increase the percentage of time spent in medium and high coherence score.	STAI	Between-Subjects (n=5/ group) BFB vs. Blank control; Repeated trials (4 Sess, 1 Sess /2 wk, 45min/Sess)
(Lewis et al. 2015)	HRV	BVP	IBI data HRV (not specified)	line graph line color	PC-based	Under Multimedia stressful environment	The subject is instructed to relax, focus on the breathing prompt, and attempt to keep the line in the green band.	HRV indices, PCL-C,	RCT (n=420 / group), BFB vs. Blank control; One-shot trial (2 h/Sess)
(Sarabia-Cobo 2015)	HRV	BVP	Cardiac-Coh, IBI data	Coherence Bar Chart (CBC), graphics	PC-based	Breathing exercise	Users attempt to smooth the RSA graph, increase the percentage of time spent in medium and high coherence score.	MBI, ZBI, Calculated Coherence score	Quasi-experiment (n= 42/32); BFB vs. pre-baseline; Repeated trial (12 days, 1 session/day, 20 min per session)
(Lee & Finkelstein 2015)	HRV	BVP	IBI data	Waveform, Visual symbol, Sound pitch	Portable device	Under psychomotor vigilance task	"Inhale slowly and gently until a new triangle appears in the top right, then exhale slowly".	Cognitive performance HRV	Within-subjects (n=14); BFB vs. Blank control One-shot trial (10 min/Sess);
(Ratanasiripong et al. 2015)	HRV	BVP	Cardiac-Coh,	Light color; Audio cue	Portable device	Breathing, exercise Positive emotion	The subjects learn to control the HRV through slower breathing and positive emotions	PSS, STAI, CES-D	RCT (n=30/group); BFB vs. Blank control; Repeated trials (4 weeks, 3 Sess/day)
(van der Zwan et al. 2015)	HRV	BVP	IBI data	RSA waveform, Visual symbol, Sound pitch	Portable device	Breathing exercise	"Inhale slowly and gently until a new triangle appears in the top right, then exhale slowly".	DASS, SPW	RCT (n=25 /group); BFB vs.meditation vs. physical exercise; Repeated trials (35 Sess, 1 Sess/day, 10-20 min/Sess)
(Al Osman et al. 2016)	HRV	ECG	LF/HF ratio	Game score Animation tree in the game	Mobile APP	Under a work task	Regulate breathing pattern and imagine positive scenes, invoke pleasant thoughts to improve the 'health' of the animation tree.	VAS	Within-subjects (n=12); BFB vs. Blank control; Repeated trials (5 BFB Sess)
(Munafò et al. 2016)	HRV	BVP	IBI data	Wave on-screen display	PC-based	Breathing exercise	The subjects were informed the goal is to increase the amplitude of RSA. They were instructed to regulate the breathing to achieve	SF-36, STAI, RSP, BP, GSR	RCT(n=20/group); BFB vs. Blank control; Repeated trials (5 weeks, 1 Sess/wk, 45 min /Sess)
(Morarend et al. 2011)	RSP	RSP	RSP signal	Musical pattern, e.g., duration of tone	Portable device	Breathing exercise	The user synchronizes inhalation and exhalation voluntarily with the musical feedback patterns.	VAS, CDAS, DISS,	RCT (n=40/group); BFB vs. Blank control; One-shot trial (15 min/Sess)
(Moraveji et al. 2012)	RSP	RSP	Calm Points, RSP-R,	Text and number on desktop	PC-based	Under cognitive tasks	A peripheral awareness cue of respiratory behavior from the system tray, motivates users to maintain calm respiration during work.	RSP-R, Post-interview	Within-subjects (n=14); BFB vs. Blank control; One-shot trial (30 min/Sess);
(Vidyarthi & Riecke 2013)	RSP	RSP	RSP-R, RSP-A	Reverb, Volume, Filters of sound	Ambient Sound system	Breathing exercise	The user constructs a sound environment (the feedback) through respiratory regulation. The created sound promotes relaxation.	Semi-structured Interview	Qualitative Experiment (n=39); Post-BFB interview; One-shot trial (15 min/Sess);

(Parnandi et al. 2013)	RSP	RSP	RSP-R	Game difficulty	Mobile APP	After Stroop color-word test	The user's breathing rate adapts the difficulty of the video game. Slow breathing patterns will reduce the game difficulty as a positive reward.	HRV indices, GSR, Task performance	Between-subjects (n=3/group); BFB vs. DB vs. Blank control; One-shot trial (8 min/Sess)
(Harris et al. 2014)	RSP	RSP	RSP-R	Quality of the music	Mobile APP	Breathing exercise	When the user breathes at a target slow rate, the audio contains no white noise. Faster the breath is, more noise is added.	RSP-R, interviews	Within-subjects (n=6); BFB1 vs. BFB2 vs. Blank control One-shot trial (4 min/Sess);
(Wu et al. 2015)	RSP	ECG, RSP	RSP signal	Waveform	Mobile APP	Under negative emotion stimulus	Calculate the resonant frequency when RSA reached maximum oscillation amplitude. Subject practice breathing exercise at the resonant frequency with the respiratory feedback.	RSP pattern, HRV indices	Within-subjects (n=15); BFB vs Blank control; One-shot trial (15 min/Sess)
(Bhandari et al. 2015)	RSP	RSP	RSP-R	Amplitude of white noise added to the music track	Ambient Sound system	Under simulated driving tasks	if the subject's breathing exceeds the target rate, the audio modification application adds white noise to the musical piece.	RSP-R HRV indices, GSR	RCT (n=7/group); BFB vs. Blank control; One-shot trial (10 min)
(van Rooij et al. 2016)	RSP	RSP	RSP-R RSP-A	Parameters in the game	VR device	Relaxation practice	No explicit tasks or goals for the players to attain. Promote an immersive, relaxing experience	STAI, PANAS	Pretest-post-test (n=86); BFB vs. Baseline; One-shot trial
(Feijs et al. 2013)	GSR	GSR	GSR level	Controlling parameters of the flower animation	PC-based	During milk expression task	"Try to breathe more slowly, fewer times, and more deeply. The more the flower flourishes, the more slowly or, the more deeply you are breathing."	Milk expression, STAI, GSR; Interview	Within-Subjects (n=12); BFB vs. Blank control; One-shot trial
(Snyder et al. 2015)	GSR	GSR	GSR level	Colour of ambient light	Interactive lighting	After distractor task.	MoodLight indicates the user's relaxed states with cooler colors like blue and heightened arousal levels with warm colors such as red and orange.	Preliminary interview, Observation on behaviors	Within-subjects (n=64); BFB vs. Leading feedback; One-shot trial (10 min/Sess);
(Dillon et al. 2016)	GSR	GSR	GSR level	Progress in the game.	Mobile APP	Relaxation practice	GSR data controls the game progress. The more relaxed the player, the greater the progress in the game.	BAI, UMACL, VAS, TSST, HR	RCT (n=25 /group); BFB vs. Blank control; One-shot trial (60 min/Sess)
(Strunk et al. 2009)	Multi-Modal	BVP EMG, GSR, TEMP	BVP, EMG, GSR, TEMP	Graphic display on screen	PC-based	Relaxation practice	The subjects were asked to relax as best they could. They can learn to control the direction of change for each display of physiological data	self-reports, EMG, GSR, TEMP, HR	Within-Subjects(n=63) BFB vs. false BFB One-shot trial (5 min/Sess)
(Cutshall et al. 2011)	Multi-Modal	BVP GSR	GSR data Heartbeat IBI data	Graphical curves and numbers	PC-based	Meditation practice	The users use focus, concentration, respiration regulation to achieve the goal in the game.	VAS, STAI	Pretest-post-test (n=8) ; BFB vs. Pre-baseline; Repeated trials (4 wk, 4 Sess/wk, 30 min/Sess)
(Adelbach et al. 2012)	Multi-Modal	ECG, GSR, RSP	RSP signal Heartbeat, GSR level	Physical movement architecture graphic, sound	Interactive space	Breathing exercise	The sound and LED indicate the heartbeats, the shape changes of Exo building indicate respiration, the GSR controls the visibility of graphic projection.	GSR, RSP-R, RSP-A, HRV, interviews	Within-subjects (n=12); BFB vs. Preset guidance vs. Blank control ; One-shot trial (11 min/Sess)
(Bouchard et al. 2012)	Multi-Modal	BVP, GSR	Arousal level HR	Game view, Frequency, and loudness of the sound	PC-based	Under 3D stress induction game	The users are immersed in a 3D game to induce stress and receive biofeedback on current arousal level and HR level.	Salivary cortisol, HR, Performance	RCT (n=20/ group); BFB vs.Blank control; Repeated trials (3 days, 1 Sess/day, 30 min/Sess)
(Sanchez et al. 2012)	Multi-Modal	TEMP, GSR	TEMP, GSR	Waveform numbers	Mobile APP	Imagery	Focusing on the finger where the sensor was worn and imagining that the finger was warm.	STAI	Within-subjects (n=5); BFB vs. Relaxing video; One-shot trials (10 min/Sess);

(Edvardsson et al. 2012)	Multi-Modal	BVP EDA	GSR data Heartbeat IBI data	Graphical curves and numbers	PC-based	Relaxation practice	The users practice different meditation approaches with biofeedback displays to learn the skills of self-regulation.	SAS, LESCA, ACSI	RCT (n=15/ group) ; BFB vs. Blank control; Repeated trials (9 wk, 7 Sess, 30-60 min/Sess)
(Wu et al. 2012)	Multi-Modal	ECG, BVP, RSP	RSP-signal SDNN, LF/HF	Graphics, Visual icon	Mobile APP	Breathing exercise	Find user's resonant respiratory frequency with Biofeedback, and instruct the user to do resonant respiration training	HRV indices Respiration pattern	Quasi-experiment (n= 33/ 34), BFB vs. Pre-baseline; Repeated trial (7 Sess, 1 Sess/day, 20 min/Sess)
(Kotozaki et al. 2014)	Multi-Modal	NIRS	CBF, HR,	Height of visual cue on screen, Task difficulty	PC-based	Relaxation practice	The biofeedback training aims to maintain CBF and HR level within the designated range by controlling visual cue separately or simultaneously	CES-D, PANAS, BJSQ, salivary cortisol, MRI	RCT (n=15/group); BFB vs. Blank control; Repeated trials (30 days, 1 Sess/day, 5 min /Sess)
(Chittaro & Sioni 2014)	Multi-Modal	GSR, BVP EMG	Stress level	Virtual character in the game	PC-based	Relaxation practice	The more the user is relaxed, the more the character is relaxed and the larger the final score will be.	Questionnaires	Within-Subjects (n=35); GSR BFB vs. Multimodal BFB vs. Blank control; One-shot trial (3 min/Sess)
(Pusenjak et al. 2015)	Multi-Modal	GSR, RSP, BVP, TEMP,	RSP-signal HRV, GSR, TEMP	Graphic display (BioTrace +)	PC-based	Under Stroop tasks	The subjects were instructed to control multiple physiological parameters at the same time to change the trend of data.	GSR, HR, RESP, Coherence,	RCT (n=18/group), BFB vs. Blank control; Repeated trials (8 weeks, 2 Sess/wk, 1 h /Sess)
(Meier & Welch 2016)	Multi-Modal	BVP RSP	RSP, Cardiac-Coh,	Waves on screen display, number	PC-based	Breathing exercise	The subjects are instructed to breathe at six bpm and match the pacer line with their breath data, using abdominal breathing	HRV indices, PSS, STAI, AD-AC,	Within-subjects (n=32) BFB vs. Physical Exercise vs. Blankcontrol; One-shot trial (10 min)
(Arroyo-Palacios & Slater 2016)	Multi-Modal	GSR, ECG, RSP	Arousal level	Virtual human characters	Mobile APP	With emotion regulation	Relax and slow down your physiological activity to calm the virtual humans	HR, GSR, REP-R, SAM, POMS,	Within-subjects (n=19); Activation BFB vs. Relaxation BFB; One-shot trial (12min/Sess);

Abbreviations of physiological terms: BFB= Biofeedback, RSA= respiratory sinus arrhythmia, GSR= Galvanic Skin Response, TEMP= Temperature; RSP =Respiration, RSP-A =Respiration Amplitude, RSP-R =Respiration Rate, HR=Heart rate, HRV= Heart Rate Variability, ECG= Electrocardiogram, EMG= electromyography, BP=Blood Pressure, NIRS= Near-infrared spectroscopy, CBF=cerebral blood flow, Cardiac-Coh= Cardiac Coherence score

Abbreviations of self-report instruments: STAI=State-Trait Anxiety Inventory, VAS=Visual Analogue Scale, PSS=Perceived Stress Scale, POMS=Profile of Mood States questionnaire, SAM=Self-Assessment Manikin questionnaire, CES-D=Center for Epidemiologic Studies Depression Scale, PANAS=Positive and Negative Affect Schedule, BJSQ=Brief Job Stress Questionnaire, DASS=Depression, Anxiety, and Stress Scale, SPW=Scales of Psychological Well-being, BAI= Beck Anxiety Inventory, UMACL=UWIST Mood Adjective Checklist, TSST=Trier Social Stress Test, SAS= Sport Anxiety Scale, LESCA =Life Event Scale for Collegiate Athletes, MASQ =Mood and Anxiety Symptom Questionnaire, PCL-C= PTSD Checklist Civilian Version, CSES=self-efficacy scale, MBI= Maslach Burnout Inventory; ZBI= Zarit Burden Inventory ; CDAS= Corah Dental Anxiety Scale, DISS=Dental Injection Sensitivity Survey, JAS=Jenkins activity survey, BSI= Brief Symptom Inventory, POQA=Personal and Organizational Quality Assessment, SF-36= 36-Item Short Form Health Survey, AD-AC=Activation Deactivation Adjective Checklist, TAS = Toronto Alexithymia Scale; EAQ=Emotion Awareness Questionnaire; ECQ=Emotion Control Questionnaire; ERQ= Emotion Regulation Questionnaire

Other abbreviations: PC = Personal Computer, RCT= Randomized Controlled Trial

2.3.2 Biofeedback techniques

Based on the content of biofeedback—physiological information, the biofeedback systems can be categorized into five types, see Fig 2.2. RSA (Respiratory Sinus Arrhythmia) biofeedback is a technique that presents successive IBI (Inter-Beat-Interval) data for assisting respiratory regulation. In some studies, it is regarded as a separate type of biofeedback. As the IBI data reflect the heart rate variability (HRV), in this review, RSA biofeedback is regarded as a particular type of HRV biofeedback and included in the HRV biofeedback group for the convenience of discussion. The biofeedback system that measures and presents multiple types of physiological information is referred to as a multimodal biofeedback system.

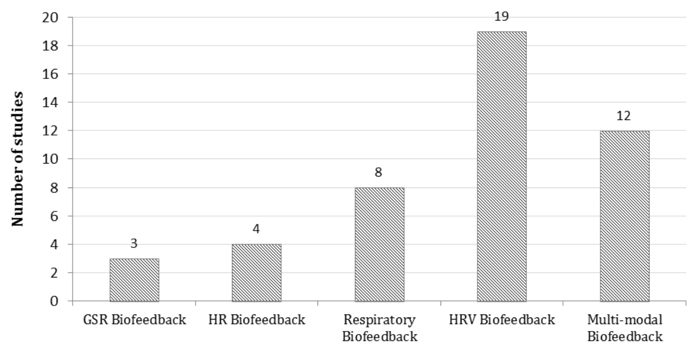

Fig 2.2 Distribution proportion of the biofeedback techniques for non-medical stress management

HRV Biofeedback (19 studies)

Heart rate variability (HRV) biofeedback (19/46) is the most common single-modal biofeedback technique for non-therapeutic stress management. Fig 2.3 summarizes a typical diagram of an HRV biofeedback system. The input of an HRV biofeedback system can be Electrocardiogram (ECG) signal or Blood Volume Pulse (BVP) signal. The content of feedback can be grouped into three types: IBI data, HRV indices, and the combination of both.

The ECG signal is the amplified heart's electrical potential that is measured by the electrodes attached to an individual's limbs and the surface of the chest. The BVP signal reflects the blood volume changes caused by the contraction of the heart. It is typically obtained by using a photoplethysmogram (PPG) sensor which illuminates the skin and detects the changes in light absorption. The ECG signal is often considered to be more accurate than the BVP signal in the calculation of inter-beat intervals (IBI) because compared to the curved peak of pulse wave, the sharp upward spike of the QRS wave in ECG signal could be detected more accurately by software algorithms. Several studies (Johnston & Mendelson 2005) have verified that when the recordings are taken during a resting state (sitting still and quietly), the IBI data calculated from ECG and BVP are highly correlated due to the improved peak detection from the pulse wave. PPG sensors have been recognized as a non-invasive, simple and cost-effective method of measuring IBI data and been widely used in commercial HRV biofeedback products, such as emWave (Lemaire et al. 2011; Ratanasiripong et al. 2015) Wild Divine (Cutshall et al. 2011; Edvardsson et al. 2012) and StressEraser (Lee & Finkelstein 2015; Moore 2006).

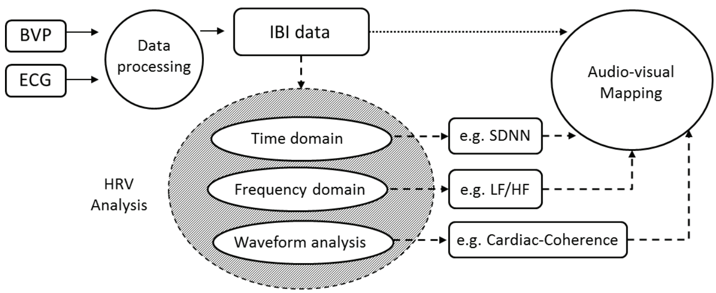

Fig 2.3
The typical diagram of an HRV biofeedback

Inter-Beat-Interval (IBI) is the time difference between two beat pulses. Heart rate varies in synchrony with respiration, by which the IBI is shortened during inspiration and prolonged during expiration (Lehrer et al. 2000). This physiologic phenomenon is referred to as Respiratory Sinus Arrhythmia (RSA). The IBI data can be modulated by breathing regulation (i.e., resonant breathing) into a sine-wave-like pattern, at which the heart rate will achieve the maximum oscillation. The immediate feedback of IBI is often used to teach users breathing skills for relaxation. This type of HRV biofeedback is also referred to as RSA biofeedback or IBI biofeedback (dotted arrow in Fig 2.3). The IBI data are usually transformed into audio-visual representations directly.

HRV refers to the variations in the IBI data. In an HRV biofeedback system, IBI data can be further analyzed to give more HRV indices (see dashed line arrows in Fig 2.3). Three main HRV indices are typically calculated for biofeedback, namely cardiac coherence, LF/HF ratio and SDNN (standard deviation of IBI data). Cardiac coherence score/value is the most common HRV index for biofeedback (Lemaire et al. 2011; Henriques et al. 2011; Mccraty et al. 2009; Whited et al. 2014; Ratanasiripong et al. 2012; Sarabia-Cobo 2015; De Jonckheere et al. 2014). Cardiac coherence describes the resonance between heart rate variations and respiratory cycles. A key marker of high cardiac coherence is the development of a smooth, sine-wave-like pattern in IBI waveform, oscillating at a low frequency of about 0.1 Hz. Therefore, in these studies, the cardiac coherence score is usually calculated by analyzing the IBI pattern. For instance, in (De Jonckheere et al. 2014), the cardiac coherence is calculated by comparing the oscillation frequency of IBI data with 0.1 Hz. A long oscillation period close to 10s contributes to a high cardiac coherence. As the promising markers of autonomic activity (Sztajzel 2004), LF/HF ratio and SDNN can reflect the balance between sympathetic and parasympathetic branches of the ANS. They can be used as an indication of stress level in a long-term ambulatory recording. However, in most studies, they are used as an indication of the relaxation training results (Al Osman et al. 2016; Zhu et al. 2012; Whited et al. 2014, Wu et al. 2012).

Respiratory (RSP) Biofeedback (8 studies)

Results of eight studies (Moraveji et al. 2012; Vidyarthi & Riecke 2013; Parnandi et al. 2013; Morarend et al. 2011; Bhandari et al. 2015; Wu et al. 2015; Harris et al. 2014) used respiratory biofeedback for stress management. Respiratory biofeedback systems measure and present the breathing-related information (i.e., depth and frequency) to help users acquire specific breathing skills for relaxation and stress relief. A typical diagram of RSP biofeedback is summarized and shown in Fig 2.4. In RSP biofeedback systems, the respiration data are usually measured by a belt-type stretch sensor which is attached to a user's thorax or abdomen measuring chest/abdomen movements (expansion/contraction). The raw data of respiration movements can be directly mapped to an audio-visual output for immediate feedback (dotted line arrow in Fig 2.4). For instance, the respiration data can manipulate a real-time sound output (Vidyarthi & Riecke 2013) or a visual pattern on screen (van Rooij et al. 2016). Furthermore, more respiratory indices, such as respiration rate and depth, can be extracted from the raw data (dashed line arrows in Fig 2.4) as the control parameters for the user interface, adjusting game scenes (van Rooij et al. 2016), adapting game difficulties (Parnandi et al. 2013), and modifying music qualities (Harris et al. 2014; Bhandari et al. 2015). In (Morarend et al. 2011), the averaged inhale and exhale time is used for synthesizing real-time musical patterns with differentiated 'inspiration' and 'expiration' sounds.

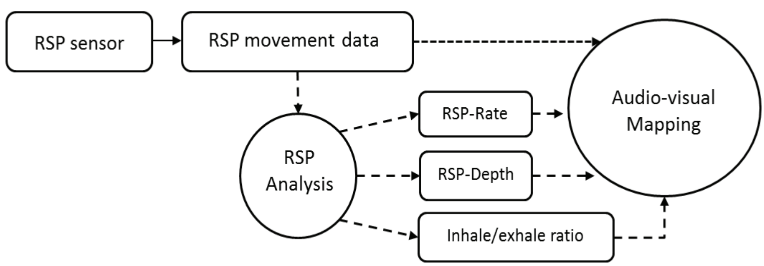

Fig 2.4 The typical diagram of respiration (RSP) biofeedback

HR Biofeedback (4 studies)

There are four studies which explored HR biofeedback for stress management. Same with HRV biofeedback, the input of an HR biofeedback system is also the ECG or BVP signal. The output is the instantaneous heart rate that can be calculated from the IBI data. The single data of heart rate is usually not sufficient to indicate an individual's stress. Thereby, HR biofeedback is used more for training the users to reduce heart rate response/reactivity to acute stresses and improve cardiac control during a stressful task, such as performing calculation work using computers (Yokoyama et al. 2002; Goodie & Larkin 2006; Larkin et al. 1992), or viewing negative pictures (Peira et al. 2014).

GSR Biofeedback (3 studies)

Galvanic skin response (GSR) has also been known as Electrodermal activity (EDA), skin conductance responses (SCRs) or skin conductance level (SCL). In this review, we use a unified term for these biofeedback systems: GSR biofeedback.

Three studies used GSR biofeedback for stress management. GSR sensors measure the subtle changes of skin conductivity which can indicate the variations in an individual's arousal levels via the autonomic nervous system. GSR feedback is usually about the trend of arousal changes. The changes of GSR data can be calculated by comparing the new GSR data to the average value of successive moving windows (Feijs et al. 2013; Dillon et al. 2016). The Least Means Squares (LMS) on successive windows of data can also be applied to determine the slope of the GSR curve (Snyder et al. 2015).

Multi-modal Biofeedback (12 studies)
Twelve studies used a multimodal biofeedback system which measures more than one type of bio-signals as the input and provides a parallel display of various physiological information or an overall result from affective computing as the output. We classify these multimodal biofeedback systems into three categories as shown in Table 2.2.

Table 2.2 Three types and their primary contents for multimodal biofeedback

Type	Biofeedback information *primary info + (secondary info)*	Studies
Dual-channel (primary and secondary)	GSR + (TEMP, HR)	(Sanchez et al. 2012),(Bouchard et al. 2012)
	IBI + (GSR)	(Cutshall et al. 2011),(Edvardsson et al. 2012)
	RSP + (HRV, GSR)	(Wu et al. 2012), (Meier & Welch 2016),(Adelbach et al. 2012)
	CBF + (HR)	(Kotozaki et al. 2014)
Multi-channel (parallel)	HRV, EMG, GSR, TEMP	(Strunk et al. 2009), (Pusenjak et al. 2015)
Affective feedback	Stress or Emotion states	(Arroyo-Palacios & Slater 2016), (Chittaro and Sioni 2014)

In the first category, eight studies used a biofeedback system that can provide dual types of bio-data. Typically, the bio-data about the physiological activity that is being regulated will serve as the primary, for instance, the GSR data in (Sanchez et al. 2012; Bouchard et al. 2012), the IBI data in (Cutshall et al. 2011; Edvardsson et al. 2012) and the RSP data in (Adelbach et al. 2012; Wu et al. 2012; Meier & Welch 2016). The other bio-data serves as the secondary information indicating the results of relaxation training or stress reduction. Two out of these twelve multimodal biofeedback studies (Strunk et al. 2009; Pusenjak et al. 2015) present four types of bio-data equally through four parallel waveform windows on the screen. Besides, in (Chittaro & Sioni 2014; Arroyo-Palacios & Slater 2016) multiple bio-data are further analyzed through affective computing to determine the emotional state or stress level of the users.

2.3.3 Biofeedback displays

We present the results about the biofeedback display from two aspects: form-giving and interactive media. The form-giving of biofeedback ranges widely from accurate graphics to casual games. In different sensory modalities, biofeedback can be presented through various interactive media: vision (e.g., screens, ambient lights, or head-mounted displays), hearing (e.g., speakers or headphones), haptics (e.g., vibrotactile actuators), or a combination of them.

Form-giving

As shown in Fig 2.5(a), most studies (38/46) employed visual displays, in which traditional graphic or numeric displays comprise a high percentage (e.g., Cutshall et al. 2011; Sanchez et al. 2012; Wu et al. 2015). Besides technical or medical graphics, biofeedback data are also represented in a more casually visual form. For instance, HRV or GSR data are visualized by an animation of a living plant, such as a tree (Al Osman et al. 2016) or a flower (Kierkels, J. et al. 2013). Biofeedback data are also mapped to some visual elements in a relaxing nature scene, including a meadow (De Jonckheere et al. 2014), a beach (Gaggioli et al. 2014), and an underwater environment (van Rooij et al. 2016). A virtual character is often used to express a user's stress and emotional states (Arroyo-Palacios & Slater 2016; Chittaro & Sioni 2014). Moreover, to improve the motivation and engagement of users, biofeedback data are also used to modify the difficulty of a game, such as the Frozen Bubble game (Parnandi et al. 2013). Beyond screen-based displays, biofeedback can be presented in a more ambient way, such as by using ambient light (Snyder et al. 2015).

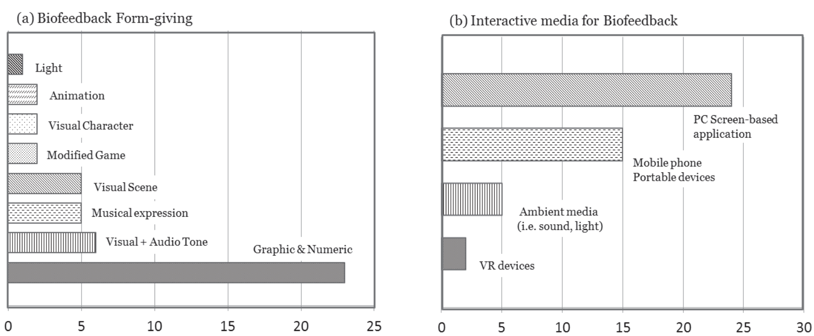

Fig 2.5

(a) The form-giving of the biofeedback systems

(b) The interactive media used in the biofeedback systems

In five studies, the biofeedback systems employed a single-modal auditory display. These auditory displays take the form of music. The biofeedback data can be directly coupled with the pitch or the intervals (between notes) of MIDI data to create music outputs (Yokoyama et al. 2002; Morarend et al. 2011). In other auditory designs, the quality of pre-selected music is modified by the biofeedback data in real time (Harris et al. 2014; Vidyarthi & Riecke 2013; Bhandari et al. 2015). As auditory displays can liberate users' eyes, these systems are often used during the work (Yokoyama et al. 2002) and some visually-demanding tasks such as driving (Bhandari et al. 2015).

Six studies used a biofeedback system that provides a combination of audio and visual displays. Biofeedback data are presented simultaneously in both auditory and visual modalities to enhance the user's perception and improve the usability of the interface. For instance, in StressEraser, the on-screen graphics combine with an audio clue to present IBI data (Lee & Finkelstein 2015; van der Zwan et al. 2015). In EmWave2, the indicator light works together with an audio cue to indicate the coherence between respiration and heart rhythm (Lemaire et al.

2011; Ratanasiripong et al. 2015). Besides, the auditory and visual modalities can be used to present different bio-data. For instance, Adelbach et al. (2012) present a biofeedback-driven adaptive architecture, where the respiration is presented by the movements of the physical structure, the heart rate is indicated by the sounds, and the GSR data is presented by the graphics projected on the ceiling.

Interactive Media

Besides the form-giving, interactive media also play an important role in user interaction with biofeedback systems. Based on the dominant interactive media in the user interface, the selected studies can be classified roughly into four categories, as shown in Fig 2.5(b). Screen-based biofeedback systems are used in the majority of the studies. The biofeedback data are displayed on the screen of a personal computer (n=24) or a mobile/portable device (n=15). Ambient media allows the users to receive biofeedback information through the surroundings in a physical environment. For instance, The GSR data can be displayed through the changes of ambient light (Snyder et al. 2015). The RSP data can be presented through a shape-changing physical structure (Adelbach et al. 2012). In recent years, Virtual Reality (VR) devices have also been used in biofeedback displays for providing an immersive and relaxing experience (van Rooij et al. 2016; Gaggioli et al. 2014).

2.3.4 Usage of biofeedback

Relaxation training with Biofeedback

Biofeedback techniques are widely used to assist various relaxation training, such as resonant breathing, positive imagery, yoga, and meditation. In those biofeedback-assisted training, users typically sit quietly and focus on self-regulation practices. The biofeedback systems serve as a tool to facilitate the acquisition of certain self-regulation skills. In most studies, the RSP and HRV biofeedback are used to improve breathing skills, including abdominal breathing (e.g., Zhu et al. 2012; Meier & Welch 2016), and resonant breathing (e.g., Paul & Garg 2012; Lemaire et al. 2011). Besides, biofeedback techniques have also been used in imagery relaxation (e.g., Sanchez et al. 2012), positive emotions (e.g., Whited et al. 2014), meditation (e.g., Cutshall et al. 2011).

Stress intervention with Biofeedback

Besides assisting relaxation training, biofeedback techniques can also be used to improve a user's the resilience to acute stress, negative emotional and mental stimuli. Typically, this type of biofeedback training is performed under or just after a simulated stressor, such as a work task (e.g., Yokoyama et al. 2002; Al Osman et al. 2016), a mental challenging task (e.g., Prinsloo et al. 2013), a negative multimedia stimulus (Goodie & Larkin 2006; Lewis et al. 2015) or a stressful game (Bouchard et al. 2012). Here, the biofeedback helps to improve the users' awareness of their stress and find a proper (mostly personalized) approach to reduce or moderate stress responses, such as arousal activities (heart rate and skin conductance responses).

2.3.5 Evaluations of effectiveness of biofeedback

Experiment design

The evaluation of biofeedback training varied widely in the selected studies. They can be broadly divided into five categories based on the approaches and the standards: Pre-Post test design, within-subjects design, between-subjects design, quasi-experiment design and Randomized Controlled Trial (RCT). Three studies (van Rooij et al. 2016; Cutshall et al. 2011; Henriques et al. 2011) designed a Pre-Post test experiment to compare the metrics before and after the biofeedback training. 18 studies followed the within-subjects design, and 23 studies used the between-subjects design (including 20 RCTs). Besides, two studies (Sarabia-Cobo 2015; Wu et al. 2012) used a quasi-experiment design, and one study (Vidyarthi & Riecke 2013) conducted a qualitative experiment through a post-test interview.

To investigate the effectiveness of biofeedback training, the evaluation usually involves a control group or a control condition for comparison. In the control group, the participants may receive a 'blank' with no feedback, bio-feedforward guidance or fake biofeedback signal as a placebo. The majority of the studies (n=33) used a blank control group. In other studies, various multimedia materials, such as a relaxing video (Sanchez et al. 2012), a pre-set relaxation guidance (De jonckheere et al. 2014; Adelbach et al. 2012; Snyder et al. 2015), or a fake biofeedback signal (Strunk, Springfield, and Burns 2009), are used as an alternative presented to the participants. Besides, other relaxation techniques can also be used for comparison with biofeedback, such as deep breathing (Parnandi et al. 2013), meditation (van der Zwan et al. 2015) and physical exercise (Meier and Welch 2016).

Metrics

Table 2.3 shows the typical metrics to assess the effectiveness of biofeedback on stress alleviation. These metrics include various measurements from four aspects: physiological measures, psychological measures, performance, and relaxing experience.

Measures	Instruments	Studies
Physiological Measures	HRV (n=18)	Yokoyama et al. 2002; Al Osman et al. 2016; Zhu et al. 2012; Wu et al. 2015; Adelbach et al. 2012; Parnandi et al. 2013; Lee & Finkelstein 2015; Lemaire et al. 2011; Purwandini Sutarto et al. 2012; Lewis et al. 2015; Paul & Garg 2012; Sarabia-Cobo 2015; Wu et al. 2012; Prinsloo et al. 2013; Mccraty et al. 2009; Meier & Welch 2016; Whited et al. 2014; Bhandari et al. 2015
	HR (n=10)	Arroyo-Palacios & Slater 2016; Lemaire et al. 2011; Dillon et al. 2016; Goodie & Larkin 2006; Bouchard et al. 2012; Larkin et al. 1992; Prinsloo et al. 2013; Strunk et al. 2009; Peira et al. 2014; Pusenjak et al. 2015
	RSP (n=9)	Arroyo-Palacios & Slater 2016; Wu et al. 2015; Adelbach et al. 2012; Moraveji et al. 2012; Wu et al. 2012; Prinsloo et al. 2013; Munafò et al. 2016; Pusenjak et al. 2015; Bhandari et al. 2015
	GSR (n=8)	Arroyo-Palacios & Slater 2016; Adelbach et al. 2012; Feijs et al. 2013; Parnandi et al. 2013; Strunk et al. 2009; Munafò et al. 2016; Pusenjak et al. 2015; Bhandari et al. 2015
	BP (n=3)	Lemaire et al. 2011; Mccraty et al. 2009; Munafò et al. 2016
	Salivary Cortisol (n=3)	Lemaire et al. 2011; Kotozaki et al. 2014; Bouchard et al. 2012
Psychological Measures	STAI (n=13)	Sanchez et al. 2012; van Rooij et al. 2016; Feijs et al. 2013; Cutshall et al. 2011; Gaggioli et al. 2014; Henriques et al. 2011; Lee et al. 2015; Paul & Garg 2012; Munafò et al. 2016; Meier & Welch 2016; Peira et al. 2014; Wells et al. 2012; Ratanasiripong et al. 2015
	RRS (n=5)	Al Osman et al. 2016; Dillon et al. 2016; Cutshall et al. 2011; Gaggioli et al. 2014; Morarend et al. 2011
	PSS (n=4)	Gaggioli et al. 2014; Meier & Welch 2016; Whited et al. 2014; Ratanasiripong et al. 2015
	DASS (n=2)	Purwandini Sutarto et al. 2012; van der Zwan et al. 2015
	PANAS (n=2)	van Rooij et al. 2016; Kotozaki et al. 2014
Performance		Yokoyama et al. 2002; Feijs et al. 2013; Parnandi et al. 2013; Lee & Finkelstein 2015; Goodie & Larkin 2006; Bouchard et al. 2012; Larkin et al. 1992
User experience	Interview	Adelbach et al. 2012; Harris et al. 2014; Snyder et al. 2015; Moraveji et al. 2012; Vidyarthi & Riecke 2013; Feijs et al. 2013; Chittaro & Sioni 2014

Table 2.3 The measurements used in the evaluation of biofeedback training

Regarding physiological measures, the common ones include HRV (18 studies), HR (10 studies), RSP (9 studies), and GSR (8 studies). HRV is the most commonly used physiological metric. In an ambulatory recording, HRV can indicate the regulatory capacity of an individual facing a stressful situation or event. In short recordings (5-15 minutes), HRV is highly related to respiratory cycles. Therefore, it better indicates the effectiveness of biofeedback on breathing regulation. HRV includes a series of parameters that are calculated from the IBI analysis in the time or frequency domain. The typical time domain parameters include SDNN, RMSSD, and pNN50. In the frequency domain, the LF/HF ratio reflects the global sympathovagal balance and therefore, is often used to indicate the balance of the autonomic nervous system.

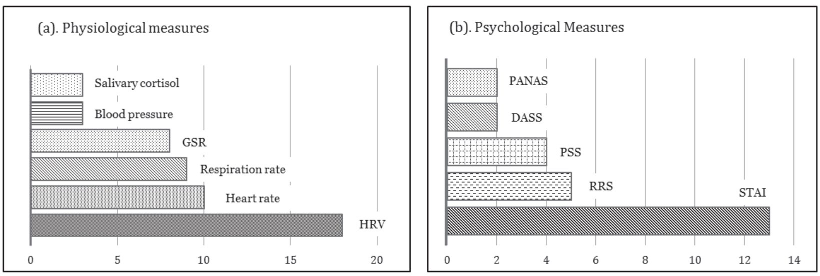

Fig 2.6
The physiological and psychological measurements used in the evaluations of biofeedback training

In a stressful situation, the body's sympathetic nervous system is activated, which quickly increases heart rate, blood pressure, and respiration rate. Therefore, heart rate and respiration rate are a simple and direct measurement of the bodily responses to stress. As shown in Table 2.3, ten studies measured the average heart rate, and nine studies measured respiration rate. The GSR signal consists of two main components: skin conductance level (SCL) and skin conductance responses (SCRs). SCL is also known as tonic level. It is continually changing and closely related to the autonomic regulation. SCRs is the phasic responses ride on the top of the tonic changes. SCRs change fast and are more sensitive to emotionally arousing stimuli and events. Most studies used the mean level of SCL as the GSR measure of autonomic regulation. Moreover, one study (Bhandari et al. 2015) used SCRs as the GSR measure of arousal level.

Various self-report instruments have been developed and widely used as psychological measures to assess stress or anxiety levels. Table 2.3 lists the common ones including STAI (13 studies), RRS (5 studies), PSS (4 studies), DASS (2 studies) and PANAS (2 studies). Thirteen studies used the State-Trait Anxiety Inventory (STAI), which has 20 items for assessing trait anxiety and 20 for state anxiety, see appendix A. The state anxiety sub-inventory (STAI-S) is often used as an indicator of perceived stress 'at the moment'. Five studies used Relaxation Rating Scale (RRS) as a simple and fast measurement, see appendix B. RRS only requires the participant to rate his/her stress or relaxation level on a Likert-type scale by circling the number that can best describe his/her current experience. Therefore, it is better suited to the experiment that needs repeated measurements or has a time limit.

Four studies used Perceived Stress Scale (PSS) to measure the perception of stress. Because the questions in PSS ask about the feelings and the thoughts during the past month, it is more suitable for measuring a general stress level in one's life and the degree to which situations in one's life are appraised as stressful. Two studies used DASS, and two studies used PANAS. Depression, Anxiety, and Stress Scale (DASS) is designed to measure three related negative emotional states of depression, anxiety, tension and stress. Each scale contains 14 items, measuring an average level of emotional states during the past week. Positive and Negative Affect Schedule (PANAS) focuses on the measurements of two mood scales: positive affect and negative affect. It consists of 20 adjectives describing a type of mood; the respondent indicates the extent he/she has felt this way over the past week. Different from STAI-S and RRS measuring an 'at-the-moment' stress feeling, PSS, DASS, and PANAS measure a general stress or anxiety level over the past one week or one month. Therefore, they are more suitable for evaluating the effects of a long-term biofeedback intervention.

In addition to the physiological and psychological measures, a user's work/task performance can also be measured to assess the effects of biofeedback. The performance measurements can be the score of a mentally challenging task including calculation work (Yokoyama et al. 2002), an arithmetic task (Goodie & Larkin 2006; Larkin et al. 1992), or a modified Stroop color-word test (Parnandi et al. 2013). The performance measurements can also be specialized by the tasks, such as a psychomotor vigilance task (Lee & Finkelstein 2015), milk expression (Feijs et al. 2013) or some behavioral indices assessed by a medical instructor (Bouchard et al. 2012). Besides, in seven studies, the qualitative data about user experience have also been collected through observations and a follow-up interview. The qualitative studies aimed to gain more insights into user experience and opinions on biofeedback systems. The interview data can be used to support the interpretation of quantitative data and provide more indications of psychological states.

2.4 Discussion

2.4.1 Discussion of biofeedback information

The biofeedback information can be classified into two types: reflecting a physiological process for assisting self-regulation (performance feedback) or indicating the results of self-regulation (result indices). For the first type, the measured bio-signals are usually processed simply and presented immediately. The immediate feedback enables the users to be aware of their current physiological activities and establish a simultaneous connection between their self-regulation and the feedback information. This connection provides grounds on which the users could develop self-regulation skills and construct knowledge through a trial and error process. For the second type, the result indices, such as HRV features, arousal level, or emotional states, can be obtained by a sophisticated approach of physiological computing or affective computing. The feedback of results information informs the users about the outcome of self-regulation or goal achievement (e.g., cardiac coherence score).

A biofeedback system may provide users with one or more types of information. Unimodal biofeedback systems are more widely used in everyday stress management. They monitor and present a specific physiological activity, including respiration, heart rate variability or arousal changes. So the user usually focuses on one single learning goal (e.g., a sine-wave-like IBI pattern) and practices specific skills (e.g., resonant breathing) to achieve it effortlessly. Because fewer bio-sensors are needed, the unimodal biofeedback devices tend to be smaller (e.g., mobile APP or portable device) and easier to operate. Multimodal biofeedback systems measure various physiological activities with a wide range of bio-sensors. They can provide richer information indicating both the performance and the results of self-regulation practice. For instance, a multimodal biofeedback system can calculate the relation between different physiological processes, such as the resonance score between HRV and respiration. However, it has also become clear from this review that the multimodal biofeedback systems require new designs of information display to facilitate the user perception and understanding of multiple feedback information and also more advanced bio-sensing techniques to improve the usability and comfort of the bio-sensors.

2.4.2 Discussion of bio-sensing techniques

Most of the biofeedback systems reviewed in this chapter still use traditional bio-sensing techniques and approaches, such as a PPG clip on the fingertip measuring the IBI and a stretch sensor on the chest measuring the respiration. We think this is mainly because the physiological signals are prone to the interference caused by body movements. The traditional bio-sensing approaches can efficiently avoid motion artifacts and improve the signal-to-noise ratio of measurements. In clinical applications, such bio-sensors and attachment approaches are acceptable. However, in everyday use, these traditional bio-sensing methods cannot satisfy user's demands for an unobtrusive and comfortable data collection. Especially for relaxation training, the wired and contact-style bio-sensors may restrict user postures, degrade user experience or even induce new stresses.

Bio-sensing techniques seem to be the first barrier between a well-proven biofeedback technique and its everyday use for stress management. Interestingly, many contactless biosensors already exist but are mostly used for monitoring, not yet for biofeedback. For instance, Adib et al.(2015) utilized a low power wireless signal to monitor the user's breathing and heart rate without body contact. Droitcour et al. (2001) developed a technology using a microwave radio for Doppler radar to sense the breathing and heart rate wirelessly. These ubiquitous sensing technologies enable biofeedback interfaces to be integrated into a home environment. Besides depending on the new bio-sensing technologies, the traditional bio-sensors can still be used, but with new wearable designs to improve their usability and comfort level. For instance, a traditional PPG sensor can be integrated into an earphone (Poh et al. 2009) or a pair of glasses (Constant et al. 2015) for unobtrusive heart rate measurement.

2.4.3 Discussion of biofeedback displays

Based on the studies reviewed, screen-based graphic interfaces are the most commonly used biofeedback display. For unimodal biofeedback systems, a graphic display or a pure auditory tone is competent in information delivery. For multimodal biofeedback systems, the concurrent feedback of multi-channel bio-data requires investing more effort into the visualization or interface design. For instance, different data can be mapped to various visual elements of the interface (De Jonckheere et al. 2014) or distributed to different sensory modalities of the display (e.g., a combination of sound, light, and physical shape changes in [Adelbach et al. 2012]).

Biofeedback displays are not only an information 'carrier' but also a stimulus influencing the user experience. For facilitating self-regulation and skill-learning, a biofeedback display should be informative. From another perspective of stress alleviation, the display should also address the following issues about the user experience. A biofeedback display can be a stimulus inducing relaxation or causing new stress adversely. For instance, in musical biofeedback interfaces (e.g., [Lundqvist et al. 2009]), the music signals not only convey information but also serve as a stimulus for promoting relaxation. A counter-example might be a phenomenon known as 'relaxation-induced anxiety', where the biofeedback displays initiate or exacerbate anxiety in some users during the relaxation training (Heide and Borkovec 1983). Fortunately, our review shows that much effort from HCI research has been made to address user experience and engagement by exploring new forms of interface, such as musical displays (Yokoyama et al. 2002; Harris et al. 2014; Vidyarthi and Riecke 2013; Morarend et al. 2011; Bhandari et al. 2015), ambient light displays (Snyder et al. 2015), VR displays (van Rooij et al. 2016; Gaggioli et al. 2014) and immersive physical environments (Adelbach et al. 2012). These new interfaces offer a more comforting and relaxing condition for biofeedback training. However, they may also require more exposure for the users to learn and adapt.

2.4.4 Discussion of the usage of biofeedback

As documented in Table 2.1, most of the current biofeedback applications still rely on a pre-scheduled training program. Although a growing number of personal biofeedback devices can be used in daily life with no need for therapist's assistance, they were still used similarly as in clinical training programs. For instance, the college students completed the HRV biofeedback training program (20 min per day, five days per week) at a dedicated office space (Henriques et al. 2011). The manufacturing operators performed five biofeedback training sessions (20 minutes) once a week in a training room of their factory (Purwandini Sutarto et al. 2012). Some training programs involve a stress-induction session before the biofeedback session. The users first perform a mentally challenging task to induce their stress responses and then learn to control and reduce the stress through the practice of self-regulation.

It has been well-proven that a long-term training program, with multiple scheduled sessions, is effective in improving the user's self-regulation skills. However, we think using biofeedback in such a way has also limited its broader application in everyday life. Beyond a tight program-based biofeedback training, we think the very potential of biofeedback might be reached with a loose and casual use. We think a stressful situation in real life offers the best timing and place to learn how to control the stress. Biofeedback can be envisioned as a small 'bio-mirror' that the users can grab from their pocket at any time to 'check' their stress level and manage the stress.

2.4.5 Discussion of the evaluation approaches for biofeedback

As shown in Table 2.3, the validation of biofeedback applications mainly depends on two types of metrics: physiological and psychological measures. The physiological data measured for biofeedback can also be stored and further analyzed into the metrics for the evaluation. In most evaluations, additional physiological measures are required to validate the biofeedback training comprehensively. In these cases, the users have to wear more bio-sensors, which largely limit the evaluations in lab settings. The psychological measures are often collected through a survey method that utilizes standardized questionnaires. The users usually complete these surveys before and after a biofeedback training. Our review shows that most of the evaluations were conducted in laboratory settings and focused on the effectiveness of biofeedback systems or training programs. To gain more insights into biofeedback design, here we suggest a long-term field evaluation method that combines the quantitative methods with qualitative methods.

Other researchers have also suggested the transition from laboratory study to field research (e.g., [Lazarus 2000]) for better understanding the people's stress and coping paradigm. Field evaluations collect the user's data outside a laboratory or a training room, where the researchers may monitor, interview and observe the users in their familiar environments. Long-term physiological measurements can offer more robust and reliable metrics to reflect the real stress level of a user. Besides, interviews in field evaluations can give high-quality data about user experience because the interviewer can adjust their questions based on the situations to clarify or get further insights. Moreover, the field evaluation also allows observing the user's behaviours, such as when and how they use biofeedback devices.

2.5 Conclusions

We conclude this chapter with two remarks. Firstly, this review may serve as a reference for other researchers and designers to better understand the current status of biofeedback techniques and their applications for stress management. The results indicate that HRV and multi-modal biofeedback systems are most commonly used for personal stress management. Screen-based visual displays are still the mainstream in biofeedback interfaces. The biofeedback applications are mainly based on a pre-scheduled training routine. The effectiveness of biofeedback is mostly assessed in laboratory settings by both physiological and psychological measurements. Secondly, through this review, we see an everyday biofeedback paradigm emerging beyond traditional clinical applications. New demands and challenges are arising as well, including an intuitive perception and correct interpretation of biofeedback information in self-use, an unobtrusive bio-sensing front-end and a ubiquitous display. We see HCI technologies might address these challenges. New interactive modalities (e.g., ambient lights, soundscape, tangible display, and haptic feedback) and related HCI theories (e.g., calm technology [Feijs and Delbressine 2017] , peripheral interaction [Bakker, van den Hoven, and Eggen 2015] and persuasive technology [Intille 2004]) can be further explored in the field of biofeedback for improving the accessibility, usability, comfort, engagement and user experience with biofeedback systems.

PART II

In this part, we explore the idea of 'Natural Coupling' between the physiological data and interface expressions in presentation mapping design. These designs aim to allow users to read and understand the biofeedback representations more effortlessly and intuitively. In chapter 3, we apply the idea of nature coupling to the design of an audio interface for heart rate variability (HRV) biofeedback. We intend to present the heart rate variability with the changing rhythm of short melodies. In this design, the timing variations of heart rate are directly mapped to the rhythmic variations in MIDI notes. In chapter 4, we present StressTree and HeartBloom, two metaphorical visualizations of HRV data. We introduce the images of tree and flower as visual metaphors in the visualization of HRV data. The traditional IBI tachogram and HRV Poincaré plots are transformed into a common flower or tree image that can be understood intuitively. Besides visualizing the IBI dataset, the appearance of the flower-shape or tree-shape visualization also represents a health-related physiological meaning semantically. In chapter 5, we present LivingSurface, an interactive wall-like surface as a shape-changing display of biofeedback. LivingSurface aims at using the qualities of a physical change to enhance the interaction with digital biofeedback information. The expressivity of LivingSurface is explored to embody the interface with a sense of life. In chapter 6, we present Breathe-with-Touch, a tactile interface that simulates human breathing movements through the inflation and deflation of an airbag. The natural coupling between the user's breathing behaviour and the interface's action is designed to facilitate an automatic breathing regulation.

3

HeartRhyme: Biofeedback through Musical Rhythm

3.1 Introduction

Heart rate is regulated by the autonomic nervous system (ANS), producing a natural heart rate rhythm. When we are under chronic stress, the ANS activates the 'fight-or-flight' response constantly, which reduces the variability in our heart rate (Anon 1994). On the contrary, greater flexibility in heart rhythm can be observed when we are relaxed. The more flexible the heart rhythm is, the more capable we are of dealing with everyday stressors. The medical term for the 'heart rhythm' is the heart rate variability (HRV). As introduced in chapter 2, HRV biofeedback systems are the most common technique for stress management. With the HRV biofeedback, people could be more aware of their heart rate rhythm and then learn to enhance it.

In a relaxation training, the inter-beat interval (IBI) biofeedback facilitates the users to improve their breathing skills for enhancing the HRV. As shown in Fig 3.1, the tachogram is commonly used by many commercial products, such as StressEraser (Moore 2006), as a visual display of IBI data. The tachogram is an example of proportional feedback, where the length of each bar represents one IBI (Feijs et al. 2010). The IBI feedback is updated with the user's heartbeat concurrently. The IBI is shortened during inspiration and prolonged during expiration. As such, the feedback of IBI data teaches the users to regulate their breathing for achieving a stable and sine-wave-like pattern on the tachogram, at which the HRV can be maximized.

In this chapter, we aim to develop a fast and explicit auditory biofeedback as an 'alternative' to the typical tachogram as shown in Fig 3.1. In audio design, we follow the approach of 'parameter-mapping' to make the sonification direct

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This chapter is largely based on

Yu, B., Feijs, L., Funk, M., & Hu, J. (2015). Designing auditory display of heart rate variability in biofeedback context. In *Proceedings of of 21th International Conference on Auditory Displays* (ICAD 2015), pp. 294-298.

and fast. We employ the idea of 'natural coupling' to make the sonification easy to perceive and understand. Four versions of auditory displays are designed and integrated into an HRV biofeedback system. An experiment was carried out to evaluate the usability of the designed auditory displays by comparing them with the traditional tachogram in a biofeedback-assisted breathing training.

Fig 3.1
A typical tachogram obtained by plotting successive inter-beat Intervals (IBI). Left: IBI visual display developed by Feijs et al. (2010) Right: the display of IBI waves in StressEraser device

3.2 Sonification Design

The sonification of heart activities is not a new idea. The most common approach to doing this is parameter-mapping (Grond & Jonathan 2011), which links the parameters of heartbeats (HR/HRV) to the parameters of sound. McCaig & Fels (2002) introduced a heartbeat-responsive music system, in which the heart rate was mapped to a scaling factor to adjust the tempo and timbre of a piece of music. The works by Avbelj (2012) sonified maternal and fetal heartbeats as musical notes in different timbres, namely a cello and a flute. The variation of heart rate is mapped to the duration of the notes. A similar example could be seen in (Yokoyama et al. 2002), a heart rate biofeedback system converts heart rate data into a piece of music with pitch and tempo changing in real-time. A more complex model-based sonification of heart rate variability has been explored by Ballora et al. (2004) for medical diagnosis. In this sonification system, multiple variables of heartbeats data were extracted as a source of musical events and further mapped to the specific pitches with different timbral annotations, such as a 'tinkling' sound or a clarinet-like timbre. Orzessek & Falkner (2006) established three different ways of HRV sonification based on frequency analysis: (1) by mapping LF/HF ratio to MIDI pitch of a constant sound; (2) mapping the amplitude of the filtered signal to the volume of sound; and (3) using the filtered signal as the MIDI note control.

In this design, our goal is to provide a fast and explicit audio IBI feedback rather than creating rich melodies. The key question is: could a similar effect be reached by using the auditory modality rather than the visual tachogram? We search for the ways of avoiding the delays from averaging windows or a complicated sonification model that involves many music parameters. Here, we use a directly parameter-mapping approach for IBI data sonification. Similar to the visual displays in Fig 3.1, each new IBI data generates an 'audio alternative' to a bar in the tachogram. Instead of being mapped to the length of the bar, the IBI data is mapped to the parameters of a sound.

The IBI, Inter-Beat-Interval, represents the time interval between two successive heartbeats. Following the idea of 'natural coupling' (Abras et al. 2004; Wensveen et al. 2004), we try to present the timing variations of heartbeat data with the timing variations in sounds instead of timbre, pitch or other acoustic properties. The rhythm of music describes a specific temporal pattern of sounds. It is about the variations in the arrangement of sounds through time. Therefore, we focus on presenting the IBI data with the rhythmical changes in a short chord. We assume the natural coupling between the heart rate variations and the rhythmical changes can be perceived by naturally and intuitively.

It seems natural to present the timing information of a heartbeat by just producing a short tone or ping upon the detection of the heartbeat event. However, the difficulty is that the difference in the IBI data is small compared to the IBI data themselves. For example, if the average IBI is 1000 ms (e.g., a 60 bpm HR), then the typical variation of two successive IBI data is less than 100 ms, which is hard to perceive by hearing. Therefore, we need to look for ways of amplifying the differences between the IBI data and making the difference easier to perceive. We deliberately avoid the full richness of music, instead focusing on the representations by one tone or a few tones only. We design some auditory representative patterns with a few MIDI notes, functioning as the bar in tachogram. In this way, the heart rate variability can be represented by the variations of rhythm in MIDI notes. Here, we proposed four promising audio-forms:

1. arpeggio chords with speed variation,
2. arpeggio chords with emphasis variation,
3. two distinct notes with inter-beat interval delay,
4. two stereophonic notes with inter-beat interval delay.

First, we present the audio-forms 1 and 2, which are easy to explain: each heartbeat is translated into one arpeggio chord of a few hundred milliseconds. We choose major scale arpeggios because minor scales tend to be associated with sadness in western culture and also because Van der Zwaag et al. (2011) found that higher arousal ratings were given to minor mode music than major mode music.

For the audio-form 1, we created MIDI files for the major G chords using notes G4, B4, and D5, as shown in Fig 3.2. The duration of one chord is N times 75 ms where N is in the range from 1 to 10. So, the shortest chord arpeggio is 75 ms, which sounds very fast and the longest one is 750 ms, which sounds very slow.

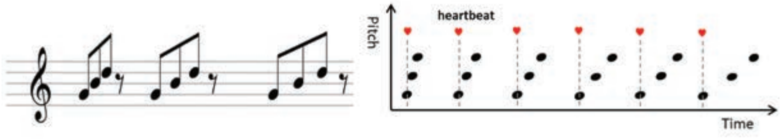

Fig 3.2 The audio-form 1: slow and fast G chord arpeggios

At each heartbeat, one chord is chosen, for which the applicable N is calculated by a linear mapping of IBI/IBI_{avg}. The linear mapping works such that the fastest chord happens when IBI/IBI_{avg} = 80% and the slowest chord when IBI/IBI_{avg} = 125%. Here IBI_{avg} is the averaged IBI obtained by a first-order low-pass filter with a time-constant of 24 heartbeats (similar to a moving-window average). If the changes are bigger, the effect is truncated at 80% and 125%, respectively. The effect is that relatively small changes in IBI variation are translated into better perceivable variations in chord length: an increase in IBI of 5%, for example, is mapped to a 20% increase in chord length. At the same time, extreme values will be mapped into truncated ranges at the ends of the spectrum.

For the audio-form 2, the timing of the chords does not vary, but one tone is accentuated, i.e., played louder than the others. Each chord consists of notes G4, B4, D5, and G5, as shown in Fig 3.3. The non-emphasized tones are played at 45% volume where 100% refers to the emphasized tone. Although we added already a fourth note to the chord, this still gives less fine-grained feedback than the previous audio-form. As before, IBI variation is calculated and then mapped to one of the four possible chords.

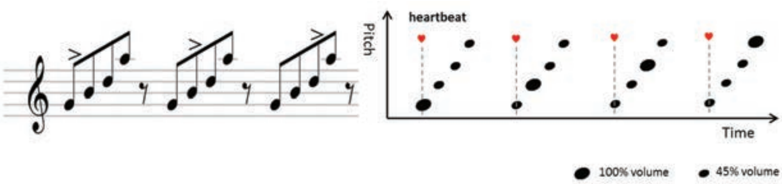

Fig 3.3
The audio-form 2: G chord arpeggios with emphasis on a different note

Next, we explain the audio-forms 3 and 4, which are based on a different idea: while the previous two audio-forms presented the length of the latest IBI, the new forms present the difference between the latest IBI and the previous one. So it is the differential of the IBIs, not the IBI itself that will be presented as sound. For this, we use two tones at a fifth interval (the notes C and G). As the heartbeat occurs, the C is played, whereas the G note is queued to be played later, the queue-delay being set to the most recent IBI data. The effect is an up-going interval (C-G) when the heart rate is accelerating and a down-going (G-C) when it slows down. The mechanism is shown in Fig 3.4(a) for one interval of duration T1 followed by a shorter interval T2, followed by a third interval T3 which is equal in length to T2 again.

The fourth audio-form is similar to the third, but now using the stereo panorama instead of the different tones, as explained in Fig 3.4(b). As one heartbeat occurs, the C is played in the left speaker, and a right-panned C note is queued to be played later on the right speaker, the queue-delay being set to the most recent IBI. The effect is a panning transition, going double-note rightward (left C–right C) when the HR is accelerating, and leftward (right C–left C) when the HR slows down.

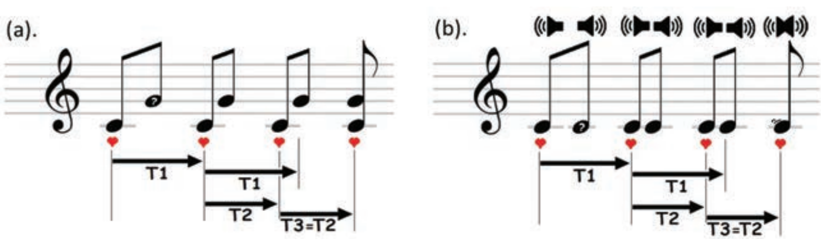

Fig 3.4
(a) GC intervals presenting accelerating and steady heartbeats
(b) Stereophonic notes presenting accelerating and steady heartbeats

3.3 User Study

A prototype HRV biofeedback system was developed to present the IBI data for assisting breathing training. The system provided four proposed auditory displays and the typical graphic display of the tachogram as shown in Fig 3.1 and described in (Feijs et al. 2010). An experiment was conducted to examine the usability of the new auditory displays. We hypothesized that they would be as effective as the tachogram and more comfortable and pleasant for breathing training.

3.3.1 Participants

We designed a within-subjects experiment with ten subjects (five females and five males, age range: 20 to 30). All subjects 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 have never received any medical HRV biofeedback training. All subjects gave the written informed consent and provided the permission for publication of photographs for scientific and educational purposes.

3.3.2 Equipment and measurements

The HRV biofeedback system is shown in Fig 3.5. A PPG sensor on the finger measures the blood volume pulse (BVP) signal. The BVP signal is processed in the Arduino program into the IBI data, which are then transmitted to the biofeedback program on the PC and further transformed into sounds or graphics. Considering the context of use, the biofeedback laboratory served as a dedicated room which provides a quiet environment for receiving auditory feedback information.

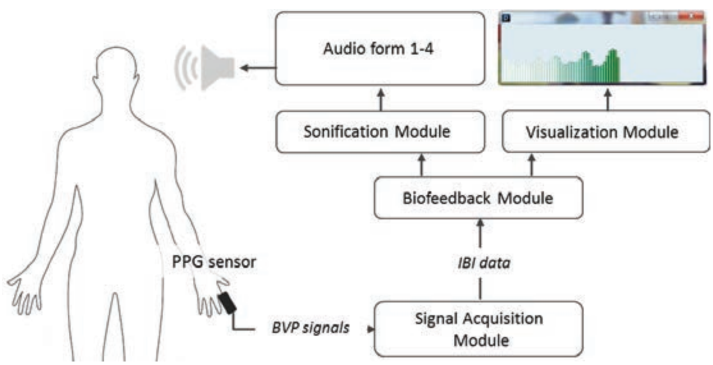

Fig 3.5 The HRV biofeedback system for the experiment

For each participant, the HRV and respiration data were collected throughout the experiment. The respiration signal was measured by a stretch (belt) sensor placed on the chest of the participant. The participants' subjective perceptions on each display were evaluated from two dimensions: *Clarity of feedback* and *Comfort of feedback*. Accordingly, the questionnaire was designed into two parts. Each part consists of three questions, see Appendix C. The participants were asked to evaluate the clarity of feedback by rating the following three questions: 1. the difficulty to understand it, 2. the difficulty to follow it and 3. how often they were lost. To evaluate the comfort of feedback, the participants were asked to rate the subjective feelings of stress, tiredness, and sleepiness. The questionnaire uses a visual analogue scale (VAS) from 1 to 5 with one being 'strongly disagree, ' and five being 'strongly agree'. After the experiment, each participant answered several open-ended questions for any comments and suggestions to improve the sonification designs. For instance, "*do you like this audio feedback? And why?*", "*Which audio-form do you like best?*" and "*In what aspects do you think the audio-form need to be improved?*"

3.3.3 Experiment design

The experiment is designed to answer two questions: 1). whether a similar effect could be reached using the auditory displays rather than the visual and 2). which of the four audio displays performs the best in term of user acceptance and assistance in breathing training? In a within-subjects experiment, all participants would complete five 10-minute breathing training tests: four with auditory biofeedback (A1: A4) and the other with the visual biofeedback (V1). The experiment randomizes the order of the five tests to counterbalance carry-over effects. The independent variable was the displays of biofeedback, while the dependent variables were the overall HRV, respiration data, and the subjective ratings. A paired-samples t-test was conducted to compare the subjective ratings and HRV data between different conditions.

3.3.4 Procedures

Before the tests, the participants watched a short video instruction to familiarize them with the HRV biofeedback system. A brief introduction was given: "*the purpose of HRV biofeedback is to perceive the variability of heart rate and learn to improve the variability by regulating breathing pattern.*" Then, the participant was instructed to relax with natural breathing for 5 minutes. This pre-test resting period is intended to obtain a baseline of HRV and respiration data without biofeedback. Next, the participant would undertake five biofeedback tests separately. Before each test, a corresponding video instruction was given to the participants for guiding them how to use feedback information to improve HRV through a breathing regulation. For the visual biofeedback test, the instructions were:

> *"The waveform represents heartbeats intervals, and it is closely related to your breathing. Try to make the waveform in a smooth sinusoidal form by adjusting your breath. You breathe more slowly and deeply, the waveform becomes more smooth and regular."*

As described above, the auditory displays were designed with different principles. Therefore, for the auditory biofeedback tests, the instructions were different but similar in style. Taking the audio-form one as an example, the instructions were:

> *"In this test, you will hear a major G chord. The duration of the chord represents heartbeat intervals, and it is related to your breathing. Try to make the chord arpeggio change from fast to slow and then to fast periodically by regulating your breath. You breathe more slowly and deeply, the changes of chord arpeggio become more smooth and regular."*

After each test, the participants answered the questionnaire and were given a 5-minute break to relax for reducing the carry-over effects. Throughout the experiment, participants were seated comfortably and instructed to move as little as possible.

3.4 Results

3.4.1 Users' perception

The results of the participants' subjective ratings on each audio-form are shown in Fig 3.6. Regarding *Clarity of feedback*, the score for the visual form (V) is significantly higher than the audio forms 2, 3 and 4 (A2, A3, A4) (p<0.05; A2, A3, A4 *vs.* V1). Regarding *Comfort of feedback*, the score for the audio-form 3 (A3) was significantly lower than the visual form (p<0.05; A3 *vs.* V1). The overall score for the audio-form 3 was significantly lower than the visual form (p<0.05; A3 *vs.* V1).

From the feedback of the open-ended questions, we found that more than 70% participants were enthusiastic about the auditory displays. In particular, they emphasized that the auditory feedback was more convenient to use because it frees the eyes of users and has a fewer restriction on the place of use. Specifically, they preferred to close their eyes when they breathe slowly and deeply for relaxation. Regarding the disadvantages, two participants mentioned that the sounds of feedback were still changing too quickly for them to perceive the pattern of the changes; this made them feel confused and even anxious. This is the main reason why they gave the audio-form low marks on *Comfort of use*.

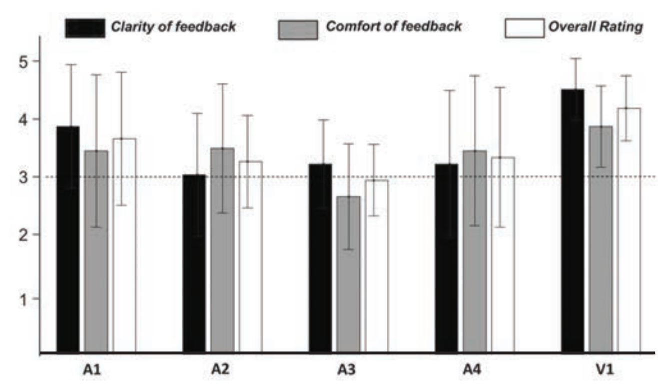

Fig 3.6
The results of the participants' subjective ratings on the audio and visual displays

3.4.2 Heart rate variability

The SDNN (standard deviation of IBI data) was calculated as the index of HRV during each test. For each participant, the SDNN of the pre-test resting period was calculated as the baseline. Comparing to the baseline, the improvement of HRV during each test was calculated and shown in Fig 3.7. The mean value of the HRV improvement in each test is denoted with a dashed line. In the biofeedback tests of A1, A2, and V1, the improvements are significant ($p<0.05$). There was no significant difference among these biofeedback tests.

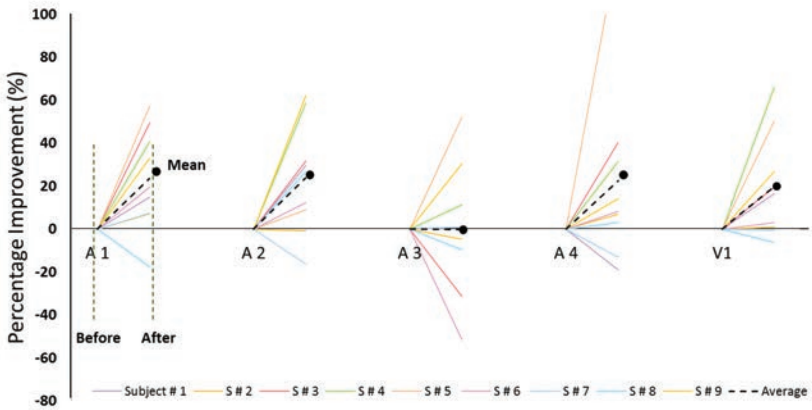

Fig 3.7
The improvements of HRV in biofeedback tests

3.4.3 Respiration

The observation on the respiratory waveform helps to understand how the participants perceive the feedback and use it to regulate their breathing patterns. Fig 3.8 shows the first-minute recording of the respiratory movement from one participant. During the pre-test resting period, his breathing is automatic and unconscious; and in the biofeedback tests, his breathing was regulated towards a deep and regular pattern with both audio and visual IBI biofeedback. In the tests of A1 and A3, the participant responded to the feedback rapidly and accurately. In A4 and V1 tests, it took the first several breathes to get familiar with the displays and then reach the similar effect. The auditory display of A2 seemed to be difficult for the participant to understand. So he failed to utilize the feedback, instead, performed deep breathing autonomously.

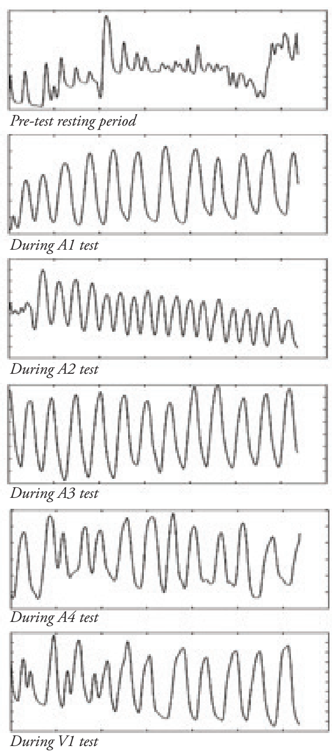

Fig 3.8
The respiration waveforms in the first minute from one participant

3.5. Discussion

In this chapter, we proposed four audio displays based on the similar principle that the variations of IBI data are mapped to the rhythmic changes of sound. The different mapping strategies have been explored. The audio-form 1 presents the IBI by changing the intervals between four notes of a chord. It is the most direct mapping between timing variations of heartbeats and the sounds. Because the rhythm of a chord can also be represented by the variations in its emphasis's position, in the audio-form 2, the emphasis of a G chord arpeggio is being modulated among four notes according to the latest IBI data. The audio-forms 3 and 4 use the interval between two successive notes to present the most recent IBI. In these two forms, the differential of the IBI data is presented as sound. The results of the user study show that the audio-form 1 received higher ratings on feedback clarity than the other three, but still lower than the traditional visual display.

The results of HRV support our hypothesis that in the biofeedback-assisted breathing training, a similar biofeedback effect (HRV improvement) could be achieved by using the auditory displays rather than the visual. The direct and fast responses of the audio displays ensured their effectiveness in conveying information. With the auditory feedback, the participants heard the sound, perceived the changes of IBI data and learned to regulate their breathing pattern to enhance the HRV. The respiration data also reflected this self-regulation process and suggested that most participants could adjust their breathing with audio feedback as same as visual feedback.

3.5.1 To improve the clarity of the auditory biofeedback display

As a presentation of information, the clarity of the designed auditory displays still needs to be improved. From the participants' ratings on *Clarity of feedback* in Fig 3.6, the visual display seemed clearer to read and easier to use than the audio-forms. In our designs, we tried to amplify the differences between the IBIs, facilitating the users to perceive the variation between two successive IBI data. The sonification process is 'heartbeat-triggered'. Each heartbeat generates a short chord instead of an individual sound or a pure tone. The parameters of IBI then manipulate the speed or emphasis of the chord, or the delay between two notes within the chord. In this way, the IBI variations are represented by the rhythmical changes of sounds. We found this might be a major difference between the visual and our audio displays. The mapping between the IBI data to the visual bars in the tachogram is 'one-to-one'. While in the audio displays, one IBI data is mapped to a chord which consists of several sounds. In other words, the mapping from the data to the sounds might be perceived as 'one-to-many', which compresses the time scale on the listener's perception. This might explain why the participants thought the audio displays were too fast or too complicated for them to understand.

Another significant difference is that the auditory displays only provide the latest IBI data while a tachogram could show both the new IBI data and also a short-term history data, see Fig 3.1. As such, the tachogram provides both concurrent and terminal feedback to some extent. A constantly visual comparison makes it easier for the viewers to find the changing pattern of the IBI data. As suggested by Hermann et al. (2011), the human auditory perception has advantages in dealing with temporal events, but the information delivered via sound tends to be transitory. It would be more difficult for the listeners to perceive the temporal pattern about how the IBI data change over time, especially when the IBI data change in a cycle of 8 seconds or longer.

3.5.2 To improve the user comfort with the auditory biofeedback displays

Regarding *Comfort of feedback*, the ratings on the auditory displays are also lower than the visual display. The participants were questioned regarding the subjective feelings of 'stress', 'tiredness', and 'sleepiness'. We found that the participants gave the audio forms high marks on 'stress'. In other words, they were feeling more tension with the audio feedback. We think there are three main reasons. Firstly, the tempo of the audio displays is strongly related to the heart rate of the participant. The auditory displays are triggered by heartbeats, same as the tachogram. For a participant who has an average heart rate of 85 bpm, she will hear the same chord 85 times in one minute. Take the audio-form two as an example; the one-minute audio display contains 340 musical notes being played. The number of musical notes will be increased to 480 per minute when the participant has a faster heart rate of 120 bpm. In contrast, a piece of relaxing music is generally characterized by a slow tempo of 60 to 80 beats per minute (bpm). For most of the participants, the sounds in the audio displays were very dense, like a piece of fast-tempo music which tends to be perceived as tense and stressful (McCraty et al. 1998).

Secondly, a few participants reported that the unfamiliarity with the newly-designed audio-forms increased their learning difficulty that caused stress. Last but not least, the aesthetic feeling of an auditory display may play an important role in the listening experience. In our designs, to achieve fast and explicit feedback, we cut the richness of music but used the simple chords as the basic audio form. As such, the audio outputs are mainly based on the pre-designed basic form (chord). The IBI data only modulate the parameters of a chord, does not modify its structure. Therefore, the final audio outputs composed of many repeated chords tend to lack in musical qualities, such as melody. This led to a feeling of tiredness for some participants. Therefore, we suggested that the parameter-mapping-based audio displays can be an audio 'alternative' to the tachogram of IBI, but still quite different from a piece of smoothing music which is arranged by a composer.

For stress mitigation and relaxation training, we think auditory biofeedback should strive for a good sound design, which is pleasant or can refer to aesthetic considerations. There are many attempts have been made to improve the musical expression for auditory interfaces. Hermann et al. (2011) suggest a model-based sonification, in which a model of a virtual music synthesizer is developed to interface with the data source and produce real-time music outputs. Real-time music notation techniques (Freeman & Colella 2010) may offer a better way to get into the essence of music and create a more melodious musical interface.

However, these techniques are still a relatively new field; few tools exist for non-composers. And also, for most HCI designers with little music knowledge and skills, it is still a challenging task to fascinate the aesthetic of a musical form for a relaxing listening experience.

One common solution for this could be using the existing well-composed music and modifying its output effects with the biofeedback data to be displayed. For instance, Bhandari et al. (2015) developed a musical biofeedback by adding white noise to a musical piece according to the user's respiration pattern. Similarly, the biofeedback system developed by Harris et al. (2014) encourages slow breathing by adjusting the quality of a piece of music in proportion to the user's respiration rate. Based on a similar idea, we developed a musical biofeedback interface by integrating the well-proven sedative music and the nature sounds. We use the nature sounds as the informative layer and the music as the background layer. The audio output sounds like a piece of New-age music. We will present more details in Appendix D.

4

HeartBloom and StressTree: Biofeedback through Metaphorical Visualization

4.1 Introduction

As documented in chapter 2, visual displays account for over 70% of the biofeedback systems. Most of these systems utilize a screen-based graphic or numeric display which often involves a specialized manual to assist users in understanding the meaning of graphs and numbers. Moreover, these traditional visual displays seem insufficient to engage the users with biofeedback data for stress management and relaxation training in everyday life. Recently, an increasing number of casual biofeedback visualizations emerge. They may become more 'playful' through gamification (Parnandi et al. 2013; Sonne & Jensen 2016) or more 'aesthetic' through artistic expressions (George 2006). Overall, we found the biofeedback visualizations tend to be close to two extremes, either too 'technical' and 'serious' in clinical applications, or too 'playful' and 'artistic' in biofeedback games and installations. Beyond representing data values, visualization could also contextualize the data to a point where they become understandable. Visualization can create images to communicate a meaningful message emerging from the data. In this chapter, we attempt to strike a balance between the two extremes by exploring a metaphorical visualization for biofeedback. We assume that a visual metaphor that is associated with life and health can help to contextualize the HRV data to make it more interpretable and meaningful.

The visualizations in a biofeedback system translate the physiological data into the visuals. For instance, the tachogram (Fig 4.1-a) represents the numerical value of IBI data with a wave diagram. The tachogram of IBI data facilitates users to regulate their breathing pattern in relaxation training. The Poincaré plot (Kamen

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This chapter is largely based on

Yu, B., Funk, M., Hu, J. and Feijs, L., 2017, June. StressTree: A Metaphorical Visualization for Biofeedback-assisted Stress Management. In *Proceedings of the 2017 Conference on Designing Interactive Systems* pp. 333-337.

et al. 1996) (Fig 4.1-b) visualizes the self-similarity of IBI data by plotting IBI(i) on the x-axis versus IBI(i+1) (the succeeding IBI) on the y-axis. The Poincaré plot shows an overall HRV, indicating the autonomic balance and chronic stress (Appelhans & Luecken 2006). As shown in Fig 4.1(c-d), a greater spread of dots means an increased HRV, while the closer the dots bunch together, the lower HRV there is. Through these visualizations, a user can read the IBI values and HRV level through the height of bars and the distribution of the dots. However, the physiological meanings and health-related information contained in these bio-data are not well expressed.

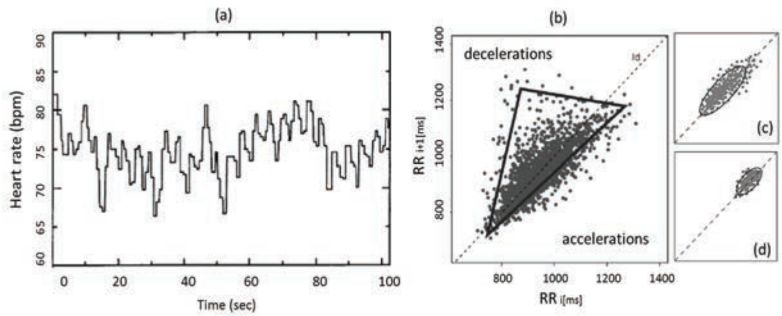


Fig 4.1
The visualizations of IBI and HRV data in clinical biofeedback (a) IBI tachogram (b) HRV Poincaré plots (c) high HRV on Poincaré plots (d) low HRV on Poincaré plots (Huebner et al. 2010)

In this chapter, we present two design cases of metaphorical visualization for HRV biofeedback—HeartBloom and StressTree. We transform the traditional IBI tachogram and Poincaré plots into an image of a flower and a tree to strengthen the semantic associations between the data and the visuals regarding health and stress. HeartBloom is designed as an alternative to the IBI tachogram (Fig 4.1-a), and StressTree can be regarded as a casual alternative to Poincaré plots (Fig 4.1-b).

4.2 Design Rationale and Considerations

Analogy and metaphor are considered as key aspects of human cognition (Gentner et al. 2001). In the expression of language, metaphors are commonly used as a way of understanding the different interpretations of the same information. Visual metaphors are often used to help the viewers to understand abstract information with some familiar and well-understood images (Blackwell & F. 2006). A good visual metaphor can help to present information expressively in a specific context (Ziemkiewicz & Kosara 2008). In some way, the external visual metaphors in data visualization can silently define a context for the correct interpretation of the information and shape its meanings.

Here, we use the images of tree and flower as a visual metaphor in visualization design, aiming to add a layer of meaning related to health and stress management. In many literary works, trees and flowering plants are often used as a typical image that is associated with life and health, such as 'the tree of life' and the 'flower of life'. A lush tree or a blooming flower is often a symbol of a healthy person, in contrast, a withered tree or a faded flower represents an unhealthy state. Our initial idea was when a user suffers from chronic stress at work; the reduced HRV will be represented by a withered and a sub-healthy visual pattern. When the user is in the right balance of stress or under a relaxing state, the visual pattern will become lush, blooming and look healthier. We are not the first to use the image of tree or flower for biofeedback representations. Feijs et al. (2013) have used an animation of a blooming flower to present the skin conductance level of a user, see Fig 4.2(a). Al Osman et al. (2016) have used a visual tree as the main character in a biofeedback game, where the animation of the leaves represents HRV level see Fig 4.2(b). In these systems, the image of the tree or flower acts as a pre-designed visual element in the interface and provides concurrent feedback in response to the biofeedback data.

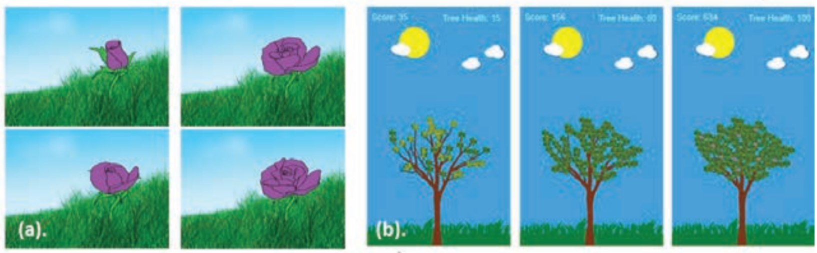


Fig 4.2
The image of flower and trees in biofeedback visualizations (a) The flower animation presents a user's arousal level (Feijs et al. 2013) (b) the tree animation present user's HRV level (Al Osman et al. 2016)

In this chapter, we do not intend to expand these ideas but to explore a novel interactive visualization, in which (1) each IBI data is visible, (2) the growing pattern can be intervened interactively, and (3) the completed visualization can metaphorically represent the health of a user as a terminal feedback. We do not address the visual presentation of a tree or a flower in a realistic way. Instead, our design, referring to the biofeedback interaction framework described in chapter 1, focuses on the presentation mapping which turns the abstract visual form (i.e., bars or dots) into a tree-shape or a flower-shape visual representation that can be interpreted semantically and appreciated aesthetically.

We delve further into the design considerations. The first goal of StressTree and HeartBloom is to visualize the IBI and HRV data into a tree and a flower image without losing neither the sight of the details nor the feeling for the composition as a whole. The value of each data and the timing sequence of the data should be visible in the whole visualization. We think this feature sets StressTree and HeartBloom apart from work by Feijs et al. (2013) and Al Osman et al. (2016). The second goal is to visualize the IBI and HRV data in real time, which enables the users to manipulate the growth pattern of StressTree and HeartBloom by self-regulation, e.g., deep breathing. This is why we base our design on the interaction model for visualization proposed by Jansen & Dragicevic (2013), instead of other visualization approaches.

4.3 Biofeedback Metaphorical Visualization

Fig 4.3 shows the visualization process for HRV biofeedback. The BVP signal is measured by a PPG sensor placed on the user's finger. The raw signal is processed into the IBI data in the *Arduino* program. The IBI data are then transmitted to the visualization program based on *Processing* platform. In the HeartBloom and StressTree visualization program, the short-term heart rate variability (HRVx) is further calculated based on a moving window of specific length (e.g., x=16 heartbeats). The IBI data and HRV index are then mapped to the parameters of abstract visual elements, e.g., the length and the direction of straight lines. In presentation mapping, these abstract visual elements are further arranged to form an image of a flower or a tree line by line.

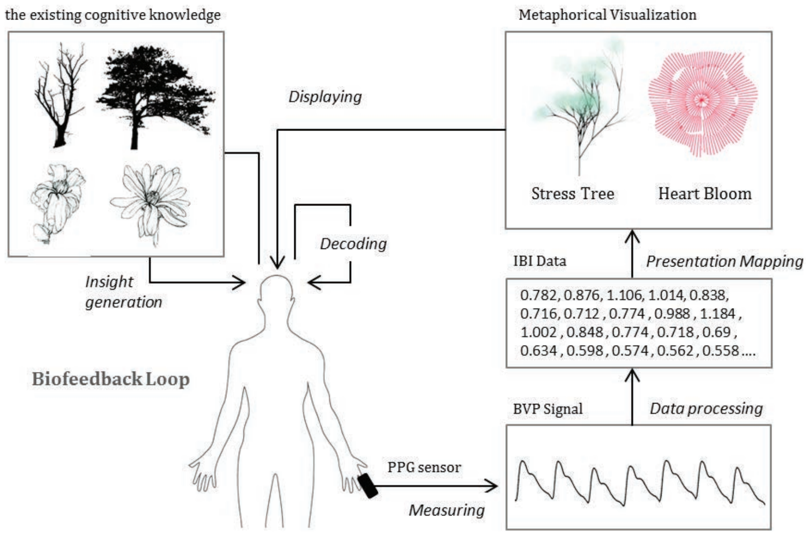


Fig 4.3 The biofeedback visualization process of StressTree and HeartBloom

Through the on-screen display, a user can watch the visual pattern of HeartBloom and StressTree growing with his/her heartbeat. The user can further extract the current IBI value from the newly generated visual element (e.g., the length of a line) and regulate the attributes of the subsequent elements during the biofeedback training. In the end, the integrated image visualizes an overall HRV which may indicate the cumulative effects of the relaxation training or long-term stress. Once being associated with existing cognitive knowledge (e.g., a lush tree mostly symbolizes health), the overall shape of HeartBloom or StressTree might be able to generate additional meanings and insights related to stress and health, which may further facilitate the users' understanding of the biofeedback data and the self-reflection on stress management.

4.4 HeartBloom

4.4.1Design and implementation

The concept of HeartBloom was to transform the IBI bars in a tachogram into an image of a flower. As shown in Fig 4.4, the visualization is formed with the basic visual element of lines. To create an aesthetic flower pattern, the lines are distributed into multiple rings and pointed towards the center. Each line represents one IBI data, same with a bar in the tachogram. Unlike the tachogram uses a horizontal axis as the timeline, HeartBloom uses a clockwise arrangement of the lines in multiple rings extending outward as the timeline. The visualization starts from the center and grows outwards continuously. After being coupled with a new IBI data, the generated line is arranged next to the previous one in a clockwise direction. When the rotation angle of the line reaches the 360 degrees, it will be placed on the next ring.

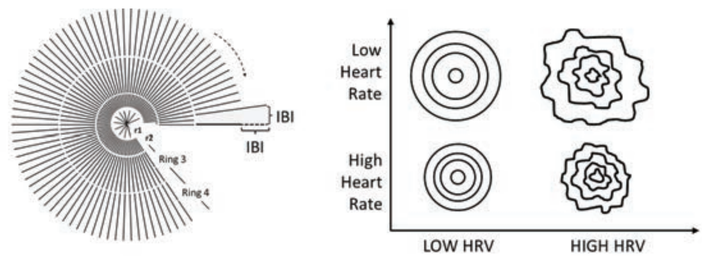


Fig 4.4
Each line represents one IBI data, and the size and shape of the flower pattern represent the overall HRV and HR

HeartBloom visualization was developed in *Processing* platform. The IBI data are mapped to the two parameters of the line: the length and the rotation angle. Firstly, we map each IBI data (from 500 to 1200 ms) to the positive or negative increment (± ½ basic width of its ring) on the length of the line. The basic width of the rings is increasing from the inner to the outer one. The larger the IBI, the longer the line. The fluctuations of IBI data make a round ring into an 'organic' shape. Secondly, the IBI data also modulate the rotation angle (± ½ basic rotation angle in each ring) of the line, which influences the density of the lines in the ring. The basic rotation angle decreases from the inner ring to the outer one; for instance, from 24 degrees in the center ring to the 4 degrees in the outermost ring. The larger the IBI value, the larger the rotation. Hence, the fluctuations of IBI data will also be reflected by the density distribution of lines.

4.4.2 Evaluation

HeartBloom can be used as an on-screen display for an HRV biofeedback system, as an alternative visual interface. In this chapter, we did not intend to compare HeartBloom with the traditional tachogram. Instead, HeartBloom visualization was used as the output of an interactive biofeedback installation, which prints the digital visualization into a physical drawing on a card. We elaborate on the design details of the installation in Appendix E. The HeartBloom installation has been shown in three international exhibitions in Dubai Design Week, (Nov 2015) New-York Design Week (May 2016) and Dutch Design Week (Oct 2016). More than 1000 participants have visualized their heartbeat data into HeartBloom flower patterns. These exhibitions allowed to demonstrate the feasibility of HeartBloom visualization with a wide range of heartbeat data.

As an HRV visualization, HeartBloom allows users to know their overall HR and HRV level by taking a glance at its appearance, and also to examine a specific fluctuation for more detailed IBI information. Fig 4.5 shows a set of typical HeartBloom visualizations collected from different participants. From the size and density of a HeartBloom pattern, it is easy to know an approximate range of heart rate: slow, modest or fast. For the same person, a small and dense pattern indicates a relatively high-arousal and stressful state, while a large and light pattern might indicate a resting and relaxing state. From its shape, it is also easy to see a user's HRV level. A reduced HRV will lead to a round-shape pattern (Fig 4.5-a). A flexible shape indicates a high HRV level. A relaxation training that involves deep breathing will generate a wholly organic 'flower' appearance as shown in Fig 4.5(b).

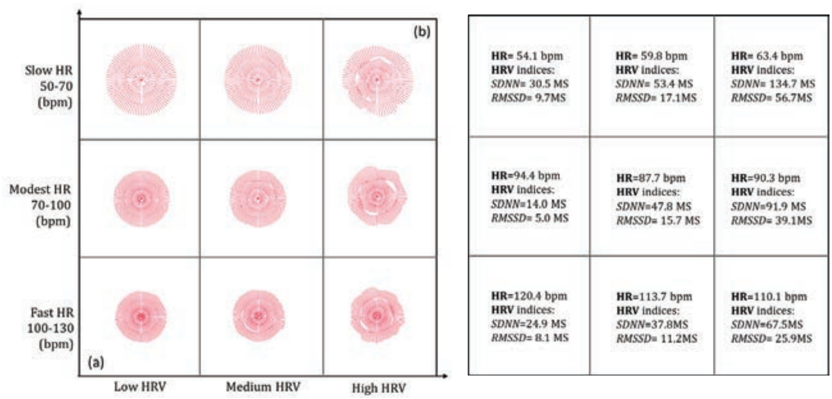


Fig 4.5
The appearance of HeartBloom represents an overall HR and HRV level. (a) The reduced HRV leads to an intensive round-pattern (b) The relaxation training improves HRV, generating a more organic 'flower'.

Besides reflecting the overall HR and HRV through the appearance of flower pattern, the specific fluctuations in its shape can also reveal a user's emotional or physical changes over time. The red parts in Fig 4.6 show some typical user behaviors during the interaction, such as relax quietly, doing physical activities, laughing and talking, and taking a few deep breaths. Following the 'spiral' timeline of HeartBloom, it is possible for the users to see the impact of their behaviors on HRV. Based on this characteristic, we think HeartBloom can well facilitate the users' self-reflection on their stress-induced events and behaviors, contributing to stress management.

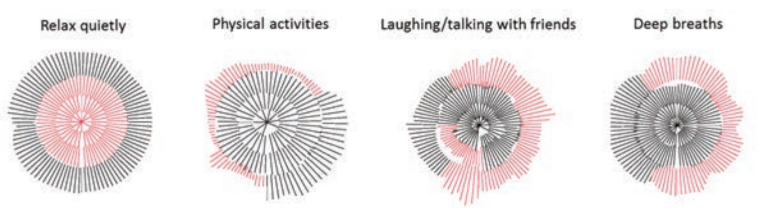


Fig 4.6
The specific fluctuations of HeartBloom represent the user's emotional and physical changes over time

In the exhibitions, we were pleasantly surprised that HeartBloom significantly stimulated the enthusiasm of the viewers. As shown in Fig 4.7, the participants appreciated it, talked about it and valued it. HeartBloom shows the value of aesthetics in personal data visualization for biofeedback. As everyone desires to create a beautiful flower, most participants were motivated to concentrate and perform deep breathing for controlling the visualization process. Many participants treasured their heartbeat data due to the uniqueness and aesthetic appearance of HeartBloom. For instance, some participants mentioned *"I would like to share it on my Facebook,"* *"it is so beautiful, can I keep it ?"* or *"I would like to send this card to my wife."*

Fig 4.7
The participants visualized their heartbeat data with HeartBloom during Dubai DesignWeek, Nov, 2015

4.5 StressTree

In this section, we present the design and the evaluation of StressTree. We experimented with two approaches in the visualization of StressTree. One is a static StressTree based on L-system (Prusinkiewicz & Aristid 1996). It can only reflect the overall HR and HRV level of a complete data collection. The other is an interactively growing StressTree generated gradually with the real-time IBI data. Different from HeartBloom, StressTree focuses more on the representation of overall HRV for a period. It might be regarded as an alternative to Poincaré plots (Fig 4.1-b) but in a more sense-making or meaning-generating way.

4.5.1 L-system StressTree (L-StressTree)

To create a tree-shape visualization, we started with the Lindenmayer system (L-system), which is widely used to model a plant growth process (Prusinkiewicz & Aristid 1996). The recursive nature of the L-system makes it easy to describe a self-similar and fractal-like form. With a certain recursion level, the L-system can generate a natural-looking organic form and artificial life. An L-system consists of two essential pieces: an axiom (w), and a set of productions (p). The axiom is the starting point, like a seed. The set of productions are the rules. For instance, when the productions are applied to the axiom: a line, they produce more lines which (along with the axiom) will also follow the production rules. The L-system StressTree is modeled using non-axial binary tree production as follows:

w : F
p : F=SF[–F][+F]

- F : Move forward creating geometry
- S: Decrement current length
- + : Turn left by an angle
- – : Turn right by an angle
- [: Push the current state (i.e., start a new command sequence)
-] : Pop the current state (i.e., execute previous command sequence

To make the L-StressTree look realistic, we set the number of recursion to 12. The length of the line is proportionally reduced in each generation with the scale of 0.8. The mapping between the parameters of the L-system and the HRV data is shown in Fig 4.8. The averaged HR determines the length of the first line. A slower heart rate leads to longer branches. The turning angle of each line is randomized within the range from zero to the maximum angle that is determined by the overall SDNN value. The maximum branch angle ranges from 4.5 to 9 degrees corresponding to the SDNN from 10 to140 ms. As such, a higher HRV will lead to a broader crown.

Parameters of L-system	HRV data
Length of the first branch: *200-50 pixels*	Averaged HR: *50-120 bpm*
Range of branch angle variation: *[0, PI/40]—[0, PI/20]*	SDNN: *10-140ms*

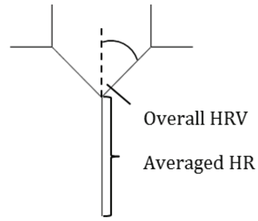


Fig 4.8
The mapping between the parameters of the L-system and the HRV data

L-StressTree is created by a pre-defined tree generator with two inputs: the average HR and SDNN, which are calculated from the complete IBI dataset. As shown in Fig 4.9, a set of L-StressTrees were created with the same dataset that was used in the HeartBloom visualizations (see Fig 4.5). Similar to the HeartBloom patterns, the appearance of L-StressTree can well represent an overall level of HR and HRV. For instance, when a user is under stress over a period, the fast HR (>120 bpm) and low HRV (SDNN<60 ms) will create a small and thin StressTree (a). In contrast, when the user is under relaxation with deep breathing, the slow HR (< 70 bpm) and high HRV (SDNN>120 ms) will create a tall and lush StressTree (b). The L-StressTree can neither show each IBI value nor manipulate its growth process in real time. For a biofeedback system, it can only provide terminal feedback by generating a static tree image after the training for example. Next, we explore an interactive way of visualizing the real-time IBI data into a tree-shaped pattern, which allows users to control its growth during a biofeedback training.

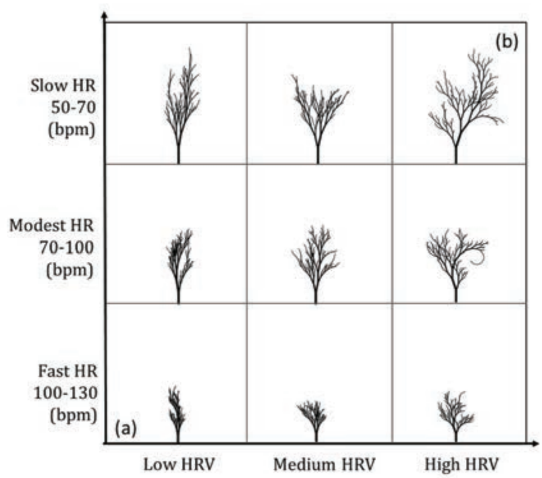


Fig 4.9
a set of L-StressTrees created with the IBI data reflecting different HR and HRV level

4.5.2 Interactive StressTree

To achieve a similar function of HeartBloom that can provide both concurrent and terminal feedback, an interactive StressTree was designed to display IBI data in real time. Two parameters, IBI_{avg} and HRV_{16} are calculated based on a moving window of 16 heartbeats. IBI_{avg} denotes the average of IBI in the window: $IBI_{avg} = (15 \times IBI_{avg} + IBI)/16$. The initial value of IBI_{avg} is 600 ms. To calculate real-time HRV_{16}, we use the following equation: $HRV_{16} = ((15 \times HRV_{16} + |IBI - IBI_{avg}|)/16)$. The growth of StressTree is triggered by the user's heartbeat. The IBI_{avg} and HRV_{16}

are updated with the heartbeats and mapped to the rules for tree generation as shown in Fig 4.10.

Each heartbeat brings one growth opportunity in one node, while HRV_{16} (0-225ms) determines the number of split in this growth. When HRV_{16} is less than 40 ms, no new branches are sprouted. Instead, a higher HRV_{16} will give more opportunities of sprouting (up to three at each node). HRV_{16} is also mapped to the rotation range of each branch. In the initial stage of growth (here we set to 4 minutes), a bigger HRV_{16} leads to a smaller angle of spread (-PI/8 to PI/8), making the branches growing upward. In the middle and last stages, a bigger HRV_{16} leads to a large rotation angle (-PI/4 to PI/4), making the branches spread out widely. The updated IBI_{avg} determines the length of the new branches. When the user is relaxed with deep breathing, IBI_{avg} tends to vary widely (e.g., 700-1000 ms) and show an approximately sinusoidal form. A sequence of flexible IBI_{avg} data yield a rich hierarchy of branches. At the end of visualization, the overall SDNN of the collected IBI dataset is calculated to determine the color of the leaves, ranging from a yellow-green to a dark-green color. The larger SDNN value, deeper the greener the leaves' color.

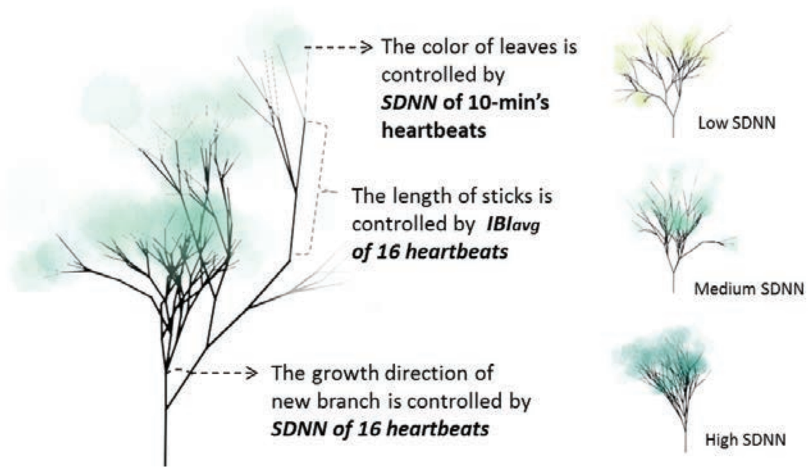


Fig 4.10
The interactive StressTree generated by the IBI data and the short-term HRV

4.5.3 Evaluation

We evaluated StressTree with ten participants. Their HRV data were visualized with StressTree under two conditions: 10-minute work and 10-minute relaxation. In the work condition, the participants did a fast-reading task that requires them to quickly complete the summary of an academic paper. In the relaxation condition, the participants sat on a rest chair to relax quietly. To not interrupt participants in the fast-reading task, the visualization of StressTree was projected on the office's wall, as shown in Fig 4.11. In both conditions, the participants were told that the growth of StressTree was associated with their HRV level. When they were relaxed, StressTree would grow upward with more branches. They were encouraged to influence its growth through deep breathing. After these two tests, we showed the created StressTrees to the participants and conducted a semi-structured interview with the following questions: "*Can you discern the HRV level by comparing two StressTrees? Do you think the StressTree can express the stress level you felt during the tests? How can you see the StressTree being used in the future?*"

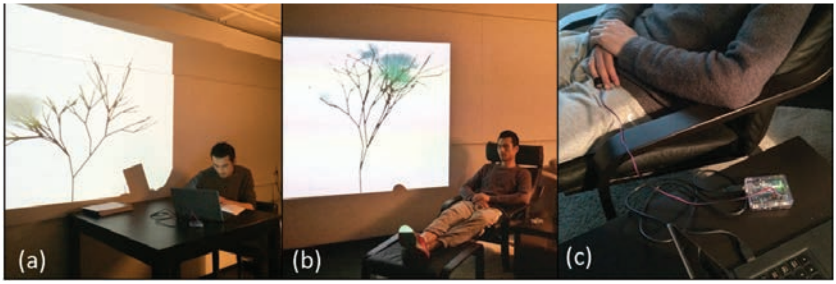
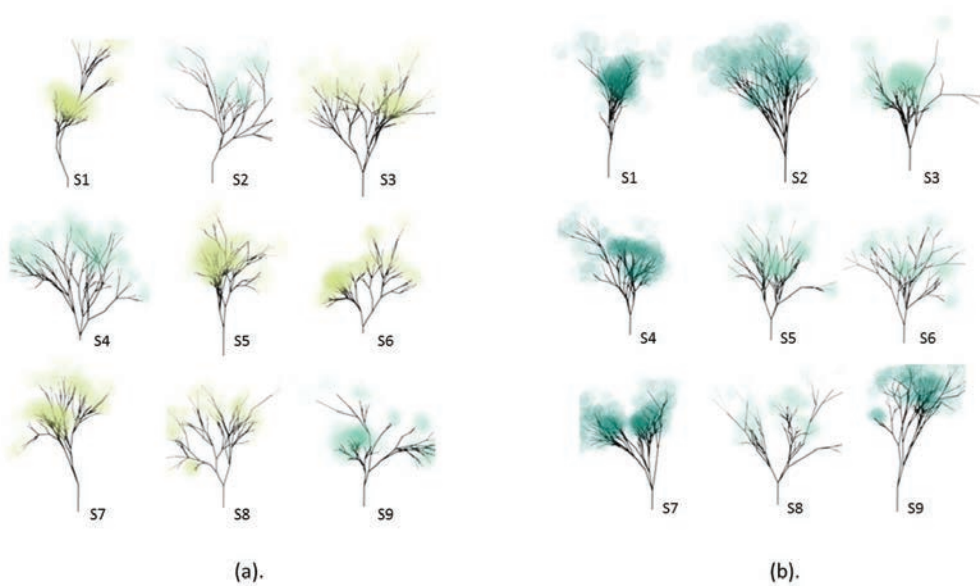


Fig 4.11 (a) StressTree during the work condition (b) StressTree during the relaxation condition (c) a PPG sensor placed on the participant's finger

Fig 4.12 shows the StressTrees from nine participants collected during the work and the relaxation conditions. The appearance of the collected StressTrees varies from a small and crooked tree to a tall and upward-growing one with more branches and dark-green leaves. Different from HeartBloom, StressTree cannot represent the heart rate level, and the IBI changes along with a clear timeline because the heartbeats and the branches are not one-to-one mapped. Instead, StressTree focuses on portraying the HRV level. The reduced HRV under the stressful work led to a scrubby shape, scanty branches, and yellow leaves as the StressTree grew up. In contrast, during relaxation, the created StressTrees looked taller and more flourish due to an improved HRV. The comparison between two groups of StressTree indicates its potential to visualize the impact of work-related stress on our health.

Fig 4.12 (a) The StressTrees collected during stressful work (b) The StressTrees collected during relaxation



In this section, we report the responses collected from the interviews. 9/10 participants reported that it was easy to identify the differences between their two StressTrees by the color of leaves, the density of branches and the shape of the tree crown. They thought the leaves' color was the most obvious difference. 8/10 participants stated that the StressTrees could well represent their state of stress during the tests. 6/10 stated that it was very natural to associate the 'health' of StressTree to their own stress level. 5/10 mentioned that the StressTrees made them more aware of how different their heartbeats were during the work and relaxation. For instance, some participants mentioned, "*I never knew that my heartbeat was so different during the work and relaxation*." They also emphasized that the 'unhealthy' look of the StressTree would motivate them to manage their stress for a 'healthy-looking' tree. Like one participant described "*I totally focused on the reading task, if I early noticed it, I would certainly change the way it grows to make it look more healthy.*" 8/10 participants thought the StressTree could be a good 'accompaniment' for relaxation training because it helped them to concentrate, reduce negative thoughts and clear the mind. For instance, one participant stated that "*it is quite relaxing watching the StressTree gradually growing with my heartbeat and being influenced by my breathing*."

4/10 participants mentioned that the display of StressTree on the wall is an acceptable way for stress intervention in the workplace. More participants (8/10) suggested that StressTree would be a great way to visualize health-related data on smartphones or smart-watches, especially for long-term personal health management. For instance, some participants mentioned "*I can see it as an application on smartwatch, the watch measures my heart rate and visualizes it with StressTree on the screen to remind me to manage my stress and relax more.*" and "*I think it would be suitable for some long-term health management APPs, I would like to see, for example, my running or heart rate data, with a tree instead of the graphics*".

4.6 Discussion

In this chapter, we explored two metaphorical visualizations for HRV biofeedback. According to the biofeedback interaction framework (in chapter 1, Fig 1.2), in audio-visual mapping, the IBI and HRV data are coupled with a basic visual element—lines. In presentation mapping, the lines are further arranged into a more representational form which looks like an image of a flower or a tree. HeartBloom visualizes the IBI data explicitly. It can provide a concurrent IBI feedback and also a terminal feedback regarding the HRV level. We argue that it can serve as an alternative to the traditional tachogram for HRV biofeedback. StressTree visualizes the HRV data more implicitly. It shows the potential to visualize an overall stress level for stress intervention. Both of HeartBloom and StressTree can be an engaging 'accompaniment' for relaxation training. We conclude with a discussion on two positive aspects of the metaphorical visualization for personal biofeedback applications.

Firstly, the metaphorical visualization may facilitate user's understanding of the biofeedback data. A well-fitting visual metaphor can be a 'bridge' between the physiological data and their meanings associated with health. Today, personal data (i.e., bio-data or physical activity data) are increasingly accessible due to wearable sensors and mobile devices (i.e., smartwatch, phone, tablet) in everyday life. Beyond numeric and graphic displays, a new form of visualization is required by a growing number of personal healthcare applications. We suggest that the new visualizations for everyday use should be easy to understand. The visuals should talk for the data, canceling the necessity of explaining. HeartBloom and StressTree presented in this chapter may serve as a design probe on transforming the traditional graphic visualizations into a more evocative and meaningful form by using a visual metaphor.

Secondly, HeartBloom and StressTree also reveal the advantages of metaphorical visualization in motivating and engaging users in long-term self-regulation and behavior changes for health. We observed HeartBloom greatly motivated the participants to regulate their interactive behaviors for a 'healthy-looking' flower. We think that the visualization of personal data based on an image from nature has the potential as a Persuasive Technology (Intille 2004), making the user feel more motivated and engaged to 'take care' of their health.

Fig 4.13 The illustrations of HeartBloom and StressTree for personal health management in the future

5

LivingSurface: Biofeedback though Shape-changing Displays

5.1 Introduction

Shape changes are increasingly used in new types of user interfaces. Shape-changing interfaces use the qualities of physical change to enhance the interaction with digital information (Rasmussen et al. 2012). In some cases, shape changes are used as both input and output of an interactive system for user interaction. For instance, Materiable responds to a direct touch by changing its shape (Nakagaki et al. 2016). In more cases, users do not deform the interface directly, the shape changes purely for information display. For instance, in Pinwheels (Ishii et al. 2001), the system monitors human behavior as the input and spins its wheels responding to specific activities in the environment. Another instance relevant to biofeedback is ExoBuilding (Adelbach et al. 2012), where the user's respiration movement is transformed into the shape changes of an architecture prototype. In other shape-changing displays (Togler et al. 2009; Kim et al. 2008; Leithinger & Ishii 2010), the orientation, volume, and texture of the interfaces are dynamically coupled with various information sources including water consumption, heartbeats, and geographical terrain.

In this chapter, we present the concept, design, and implementation of LivingSurface, a shape-changing interface for biofeedback display. We designed a set of paper-based surfaces that can vibrate, swing, bulge, or rotate to evolve into a three-dimensional structure on their cutout patterns. By taking the real-time bio-data as the input, LivingSurface reflects a user's internal physiological activities through its dynamic shape changes. We were curious about whether the expressions of a shape-changing interface could 1) embody the interface with a

This chapter is largely based on

Yu, B., Bongers, N., Van Asseldonk, A., Hu, J., Funk, M. and Feijs, L., (2016) LivingSurface: Biofeedback through Shape-changing Display. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI'16), pp. 168-175.

sense of life, 2) represent the physiological processes or states 3) and strengthen the bonding between the individuals and their bio-data. LivingSurface was designed with the following goals:

- Create a shape-changing display, providing people with the information about their internal physiological activities.
- Design the cutout patterns of a flat surface that can evolve into a three-dimensional structure by applying tension and motion.
- Explore appropriate actuating mechanisms to achieve a controllable shape change for biofeedback information display.

5.2 Design Rationale and Considerations

Physical transformations may enhance the expressivity of an interface. As suggested by Rasmussen et al. (2012), compared to on-screen digital displays, the physical transformations give a shape-changing interface two extra parameters—kinetic and expressive parameters, to couple with the information. Kinetic parameters primarily refer to the physical specifications of the transformation, including velocity, path, direction, and space. According to Rasmussen et al. (2012), the expressive parameters account for "*how the effect of the kinetic parameters are perceived*". The expressive parameters include qualities (e.g., soft, peaceful, or turbulent), personality traits (e.g., happy, sad, or depressed), and organic (nature or anthropomorphic). As we understand it, a shape-changing interface can display information by coupling its kinetic parameters with the data and exploiting its expressive parameters to contextualize the information and shape the meanings.

Our first consideration is that the shape changes of LivingSurface should be perceived as anthropomorphic or organic. Following the idea of 'natural coupling', the presentation mapping of LivingSurface is designed to generate the associations with the human physiological activities, such as heartbeat, respiration, high-arousal or calm state. We have seen several shape-changing interfaces were designed to be a 'living object'. For instance, Thrifty Faucet (Togler et al. 2009) was designed to "*move and behave in life-like manners and to step into dialogue with the user*". Kim et al. (2008) designed an inflatable mouse that can simulate the human's heartbeat by changing its tempo. The life-like shape changes are also designed to engender an emotion (e.g., [Togler et al. 2009]) or to generate an association with life and nature (e.g., [Oosterhuis & Nimish 2008]). For instance, a fast, pumping motion can usually be experienced as being tense, and a slow flowing movement can be experienced as being relaxed. The shape changes of the interface might also add more hedonic, aesthetic, and experiential qualities to the user interaction.

The second consideration is that we hope LivingSurface can blend into a living space or a home environment. We envision that LivingSurface can be both informative for biofeedback display and aesthetic as an interior decoration. As shown in Fig 5.1, the initially conceptual LivingSurface is a biofeedback 3D wallpaper, which informs the inhabitant's internal state peripherally in standby mode and assists the inhabitant's self-regulation in training mode. In this chapter, we focus on designing a shape-changing surface that can be hung on a wall as a decorative artwork. Interactive shape-changing surfaces have been explored in many studies within the field of architecture and HCI. Shutters by Coelho & Maes (2009) is a louver that is actuated by shape-memory-alloy, and the louver's elements can be addressed individually for conveying information. Murmur by Rydarowski et al. (2008) is an interactive kinetic sculpture made of one hundred computer CPU fans and paper cards. It responds to the environmental sounds with different movement patterns of the cards. BLANKET by Khoo & Salim (2013) is a responsive morphing architectural skin, which senses the environment and changes its forms as an ambient display. Davis et al. (2013) designed a shape-changing wall panel named TextileMirror which changes its shape in response to the user's emotions.

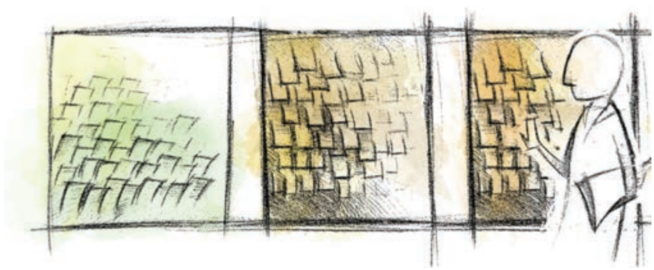


Fig 5.1
The initial design concept of LivingSurface as a biofeedback 3D wallpaper, Image by Xu Lin

5.3 LivingSurface Biofeedback System

5.3.1 System framework

In essence, LivingSurface is a biofeedback interface that takes a user's bio-data as the input and exploits its shape changes as the output. Fig 5.2 shows the basic structure of LivingSurface biofeedback system. Blood Volume Pulse (BVP) signal is measured by a PPG sensor and transmitted an Arduino program where the IBI and HRV data are further calculated for biofeedback. In the presentation mapping, the IBI and HRV data are coupled with the controlling parameters of the actuators, driving the surfaces to perform shape-changing expressions.

The surface design consists of two layers: a pattern layer (front layer) and an actuating layer (back layer). The pattern layer is a piece of regular paper that is laser-cut with repetitive incisions. With different connections, the actuating layer transforms the force from different actuators (vibration motors, CPU fans, and servo motors) into action on the pattern layer, changing the 2D layer into a 3D object.

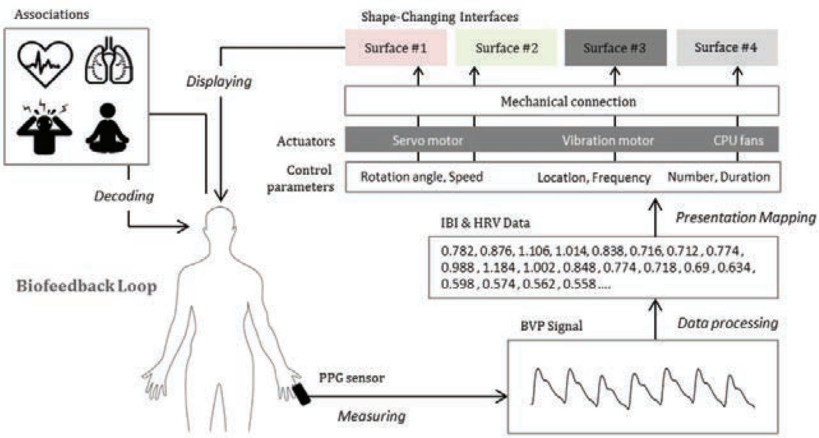


Fig 5.2
The system structure of LivingSurface

5.3.2 Biofeedback data

Similar to the previous work, LivingSurface is also interfaced with an HRV biofeedback system, displaying the IBI and HRV data. The data are updated with each new heartbeat but smoothened with a moving window. IBI_3 is the average of the IBI in a moving window of three heartbeats. The formula is $IBI_3 = (2\times IBI_3+IBI)/3$. We calculate the HRV of the latest 16 heartbeats to indicate a short-term HRV level. The formulas are $HRV_{16} = (15\times HRV_{16}+|IBI-IBI_{avg}|)/16$ and $IBI_{avg} = (15\times IBI_{avg}+IBI)/16$. The initial value of IBI_3 and IBI_{avg} is 600 ms. The mapping between IBI_3 and HRV_{16} to the shape changes for each surface will be explained separately in the next sections.

5.4 Implementation of LivingSurface

The design of LivingSurface was based on the collaboration with Alissa van Asseldonk and Nienke Bongers from ALISSA+NIENKE STUDIO[1]. We took inspirations from origami, paper sculpture, and plane composition to create a shape change from a 2D plane to a 3D structure. We first selected the material for the pattern layer. Here we used a regular paper due to its affordability, usability, and ability of shaping. We experimented with different repetitive incisions on the pattern layer based on the following two considerations: one is the aesthetics of the pattern, both in a stationary state and in dynamic movements; the other one is its ability to deform and recover. Next, we thought about how to present the biofeedback data through the shape changes of the pattern layer. To make LivingSurface look ‘living’, the dynamic expression was specifically designed for

1. ALISSA+NIENKE STUDIO, http://www.alissanienke.nl/, retrieved:13-11-2017.

Fig 5.3 the prototypes of the LivingSurface in their 3D deformations

different pattern layer to simulate a particular physiological activity with consistent semantics. Then, for each pattern layer, we developed the matched actuating layer to transform the actions of actuators into tension or motion on the pattern layer. This includes the design of the connection, the mechanical structure, and the actuator control.

5.4.1 Surface #1 (S1)

For S1, the basic unit of the pattern layer is originated from classic key patterns. Each unit consists of multiple basic key patterns in different directions. We experimented with various layouts of the pattern; Fig 5.4 shows the one used in our final prototype. To achieve a uniform shaking motion, we attached the vibration motors on the supporting structures of the actuating layer instead of fixing the motors directly on the pattern layer. The actuating layer is a piece of press paper with four openings, carrying vibration motors. Each vibration motor is connected to several 'nodes' of the pattern layer via soft threads. This flexible connection helps to distribute the vibration power to a wider area and absorb excess vibration power as a buffer. For example in this prototype, there are twenty nodes on the pattern layer being connected to a total of four vibration motors on the actuating layer.

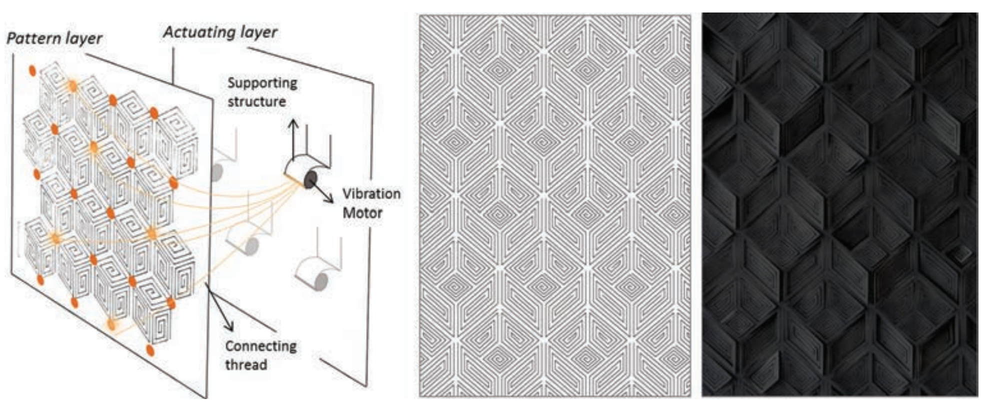


Fig 5.4 The pattern layer and connection design of Surface #1

Surface #1 represents human heartbeat activity. The presentation mapping is direct and simple. The surface vibrates in response to each heartbeat. A fast heart rate is reflected by an 'active' surface vibrating rapidly. The intensity of each vibration indicates the current short-term HRV level. As the HRV is an index of our autonomic balance and the capacity of stress coping, the expression of S1 aims to generate an association between the vibration intensity and the human's resilience and vulnerability to stress. Under chronic stress, the decreased HRV results in a weak vibration. During a relaxation with deep breathing, the enhanced HRV strengthens the vibration of the surface, which can be experienced as forceful and resilient. Specifically, each heartbeat triggers once vibration of 400 milliseconds. How many motors are actuated is determined by the HRV_{16} (0-225ms). A higher HRV_{16} activates more motors (up to 4) providing a stronger vibration. The position of the activated motors in each vibration is random.

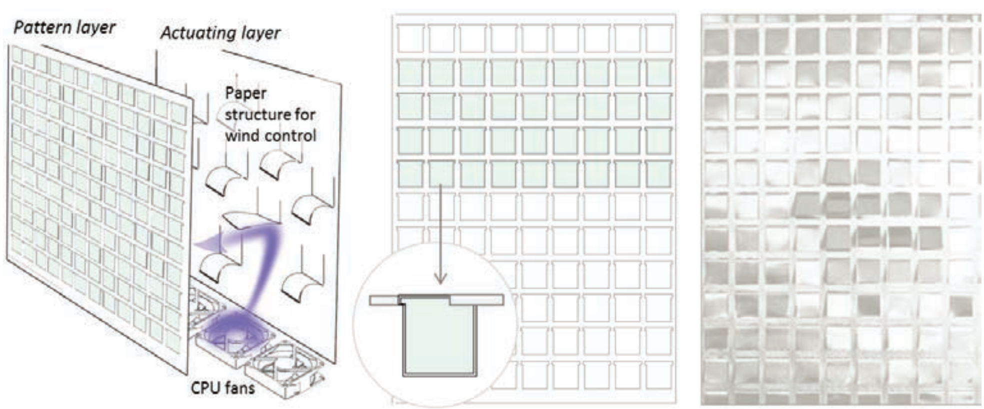
Bio-data	Expressive parameters	Kinetic parameters	Controlling parameters
	Heartbeat		Timing of Vibration
HRV16 *(0-225ms)*	Resilience to stress	Intensity of the vibrations	Number of actuated vibration motors *(0-4)*

Table 5.1 The presentation mapping for Surface #1

5.4.2 Surface #2 (S2)

For S2, the pattern layer consists of a 2D array of small 'windows' hanging on the frame. Each unit seems like a 'vertical window'. The wind from a set of DC-driven fans acts on the pattern layer as shown in Fig 5.5. The air pressure produced by the wind drives the windows to swing flexibly. Three CPU fans are fixed in the bottom, blowing the air up. The actuating layer is cut with several curled-down openings. The wind is directed towards the windows, generating a fluctuating wave effect on the surface.

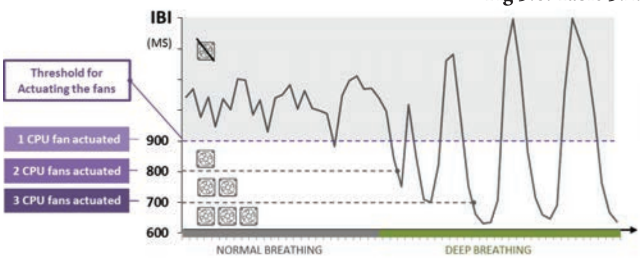
Fig 5.5 The pattern layer and connection design of Surface #2



Surface #2 represents human breathing movement with an expression of 'wind sways windows'. As shown in Fig 5.6, during a normal (shallow) breathing, the IBI oscillation is minor. By slow and deep breathing, the IBI oscillation can be greatly enhanced. The degree of IBI oscillation is closely related to an individual's breathing pattern. Therefore, S2 reflects the user's breathing pattern by indirectly visualizing the oscillation of IBI data through the surface's fluctuation. When the user breathes slowly and deeply, the windows are blown by the wind rhythmically at the same frequency of the user's breathing. Through the amplitude and the rhythm of the window's swaying, the users can see, hear, and feel their breathing.

We set the threshold of IBI for actuating the CPU fans to 900 milliseconds. At each heartbeat, the new IBI is compared to the threshold. When the user breathes in deeply, the IBI decreases, and when it becomes smaller than the threshold, the fans come into operation. Conversely, when the user breathes out, the IBI increases beyond the threshold, the fans stop and the surface becomes 'calm' again. As such, the breathing cycle can be reflected by the duration of swaying. The IBI value determines the number of the actuated CPU fans. The smaller the IBI, the more fans will be actuated, providing stronger wind blowing at the surface. To some extent, the breathing depth is reflected by the amplitude of swaying.

Fig 5.6. Table 5.2. The presentation mapping for Surface #2



Bio-data	Expressive parameters	Kinetic parameters	Controlling parameters
IBI data	Breathing cycle	Duration of the swaying	Onset and offset of the actuation
	Breathing depth	Amplitude of the swaying	Number of the actuated CPU fans

The expressions of S1 and S2 are straightforward and explicit. Through S1, the user's heartbeat activities are represented by the vibrations of the surface. Through S2, the user's breathing movements are reflected by the fluctuations on the surface—wind sways windows. However, one common problem of S1 and S2 is that their shape changes are difficult to control. The information display requires the shape changes to be controllable so that the surface can reproduce the same shape change with the same input data. We try to solve this problem in the design of S3 and S4.

5.4.3 Surface #3 (S3)

In S1 and S2, the connections between the pattern layer and the actuating layer are indirect and 'soft' (by threads and wind), which makes the motion of the cutout patterns flexible and look 'organic'. To achieve a repeatable and controllable shape change, in S3 and S4, we used a direct connection by gluing specific points of the cutout patterns to the actuating layer. The actuating layer is controlled precisely with mechanical structures and servomotors. The precise displacement of the actuating layer drives the pattern layer to produce a certain degree of 3D structure, which can be used to present information more accurately.

S3 aims to represent the IBI data more accurately so that it can be used as an alternative to the traditional IBI tachogram. As shown in Fig 5.7, a strip-shaped pattern is evenly spaced on the pattern layer. The opened side of each strip is glued to the actuating layer. The two layers are close to each other. The middle bottom of the actuating layer is connected to a gear-rack structure that transforms the rotation motion of the servomotor into vertical motion. When the actuating layer moves up, the strip-shaped segments curve and bulge outward; when the actuating layer moves down to the original position, the surface becomes flat again.

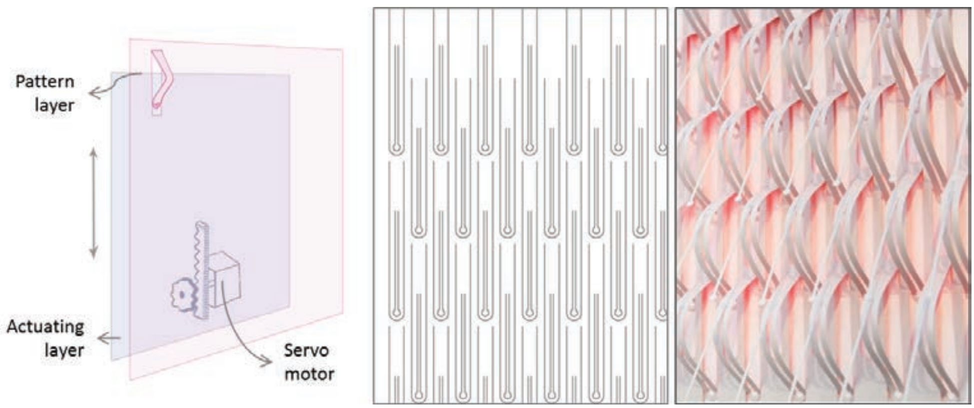


Fig 5.7 The pattern layer and connection design of Surface #3

The IBI_3 data (550-1150ms) is mapped to the rotation angle (5-175°) of the servomotor, driving an up-and-down motion of the actuating layer. Fig 5.8 shows the deformation process of S3 during a deep inhalation. When the user breathes in deeply, the surface bulges outward, and when the user breathes out deeply, the surface flattens again. During a relaxation training with deep breathing, a sine-shaped IBI waveform (see Fig 5.6) can be presented by a cyclical and smooth undulation of S3.

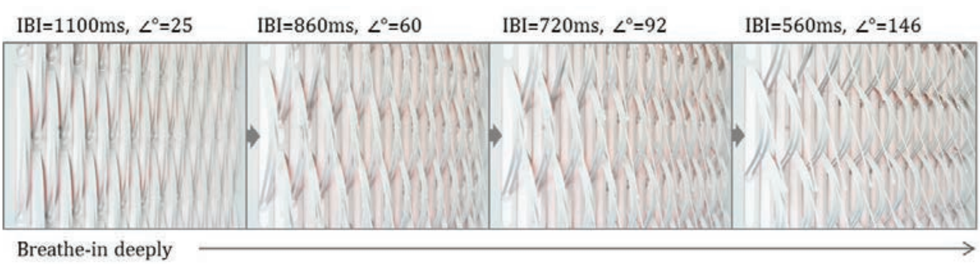


Fig 5.8 The deformation process of the Surface #3 during a deep inhalation

5.4.4 Surface #4 (S4)

For S4, the cutout on the pattern layer is a set of evenly-spaced spiral shapes. The center of each spiral is glued to the actuating layer. The displacement of the actuating layer drives the center point of the spiral out of its original position, producing a 3D helical sculpture on the surface. The further the spiral's center deviates from the original position, the more obviously the helical structure is extended outwards. Moreover, while the actuating layer is moving in different directions, the surface shows a different pattern of helical structure, see Fig 5.9 (a-c).

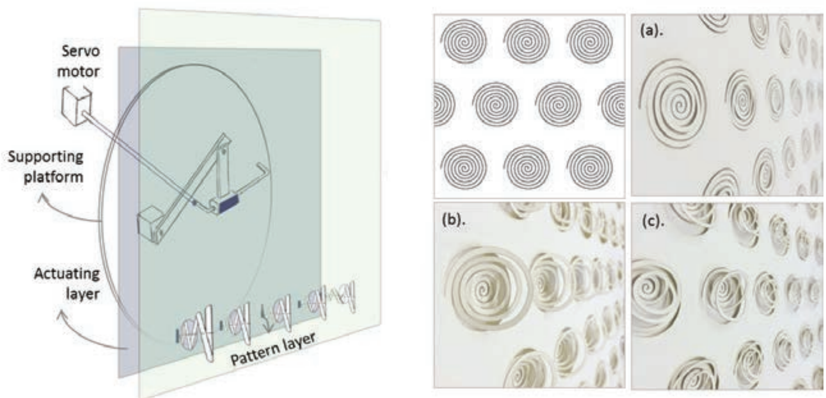
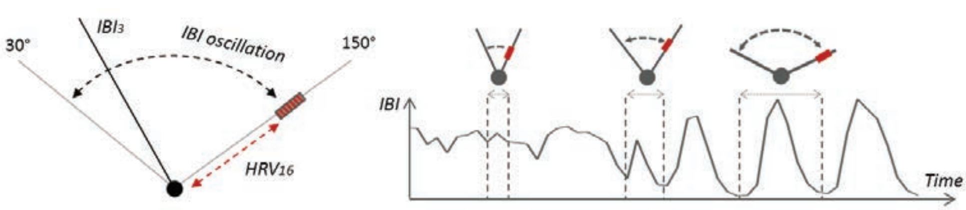


Fig 5.9
The pattern layer and connection design of Surface #4

The mechanical structure of S4 consists of two parts: a round supporting platform rotating around its center and a crank-slider structure fixed on the platform to adjust the circle radius. The center of the supporting platform is fixed on the shaft of a standard servo motor, whose speed can be adjusted. The crank-slider structure is connected with a mini servomotor whose rotation angle controls the position of the block in the slider. Compared to S3, S4 has more flexibility in motion. Under the joint action of the dual movements, the actuating layer moves in an arc path with a changing radius.

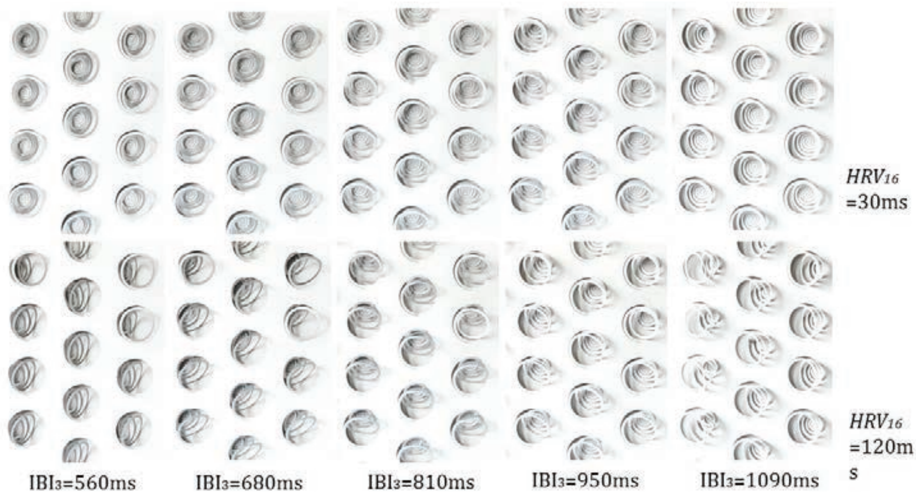


Bio-data	Expressive parameters	Kinetic parameters	Controlling parameters
IBI_3	Breathing depth	The position in the arc-shaped motion	Rotation angle of standard servo
HRV_{16}	Tension or relaxation	Closing or opening of the spiral structure	Rotation angle of mini servo

Fig 5.10. Table 5.3. The presentation mapping for Surface #4

As shown in Fig 5.10, the IBI_3 data (550-1150ms) is mapped to the rotation angle (30-150°) of the standard servomotor, which controls the angle of the actuating layer in the arc path. When the user breathes in deeply, the IBI_3 decreases. The motor rotates to the 30° position, shifting the actuating layer to the left (seen from the front). When the user breathes out, the actuating layer is shifted to the right. The range of arc-shaped motion indicates the degree of the IBI oscillation. HRV_{16} determines the radius of the arc-shaped motion. A low HRV keeps the actuating layer stays near the center, moving with a small radius. The surface looks flattened. A higher HRV drives the spiral's center to deviate from its original position further, leading to a more visible '3D' look of the deformation, as shown in Fig 5.11.

Fig 5.11 The transformation of the Surface #4 with different IBI value and at different HRV level

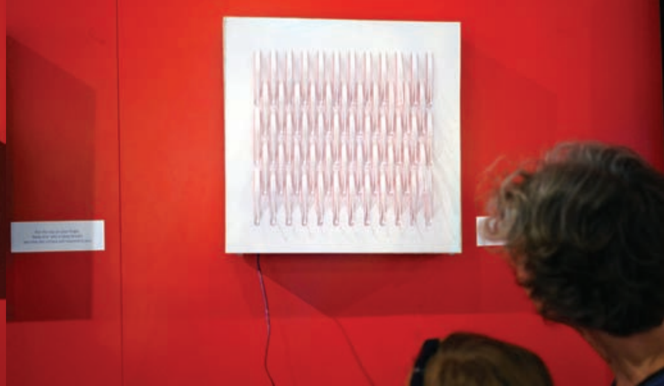


5.5 Exhibition and Feedback

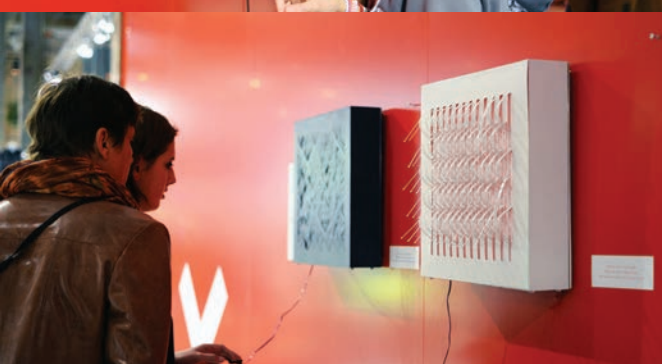
LivingSurface was installed at the *Dutch Invertuals* exhibition during Milan Design Week, Italy, in April 2015, the *Mind the Step* exhibition during Dutch Design Week, Eindhoven, October 2015 and the *Global Grad Show* during Dubai Design Week, Dubai, November 2015. The public exhibitions allowed us to observe how the visitors interacted with LivingSurface. For the exhibitions, the demos of S1, S3, and S4 were developed with three 40 cm × 40 cm ×10 cm (length, height, width) wooden frame boxes, which were hung on a wall. The mechanical structures, Arduino circuit board, and power supply were mounted inside the box, and the shape-changing surface was fixed on the outside. A PPG sensor was attached to each box for user interaction.

Fig 5.12
LivingSurface exhibited at
Milan Design Week (2015)

Fig 5.13
LivingSurface exhibited at Mind the Step, Dutch Design Week (2015)


MIND


On the exhibitions, when LivingSurface senses an absence of heartbeat data at the input, the surfaces are static, like '*an abstract painting hung on the wall*' as one visitor commented. After the participants put on the PPG sensor, the surfaces detect the valid heartbeat data and then start to move. We interviewed over 100 participants, who have interacted with the surfaces, for their feedback and comments. The participants commented on S1 as '*delicate*' and '*mysterious*' due to its thin black paper layer and complex cutout pattern. S3 and S4 were widely appreciated as a decorative artwork. The participants commented on the dynamic expressions of S3 as '*graceful*' and '*beautiful*'. The sounds of the surfaces, e.g., the papers rustled in the motion or the noise of servomotor, did not interrupt the user interaction or decrease the experience with LivingSurface. Instead, many participants thought these sounds made the surfaces more '*living*' and '*life-like*'. The following comments were made especially regarding the participants' understanding of the mapping between the biofeedback data and the shape changes of LivingSurface.

Most of the visitors thought the expression of S1 was the easiest to understand due to its explicit mapping. They could perceive the vibration associated with their heartbeat quickly. Some participants mentioned that "*it was amusing to see my heartbeat on the surface*" and "*my heartbeat looks so excited*". As we expected, many participants described S1 as an '*alive*', '*living*', '*animate*', '*organic*' object. However, most of the visitors cannot tell the difference in vibration intensity, which is controlled by the number of vibration motors and mapped to their short-term HRV level. We think there are two possible reasons for this. One is the repetitive incisions on the pattern layer make the surface prone to deformation. The surface's vibration is imperceptible visually. The other reason is that in a short interaction, the increase of HRV is minor and hard to notice. The improvement in HRV by breathing regulation takes time. We think a possible solution could be mapping the HRV to the duration of the vibration which might be easier to perceive.

The simple mapping makes S1 respond fast, but less functional in the information display. In contrast, interacting with S3 and S4 needs a physiological self-regulation process. The participants' perception and experience are to some extent dependent on their performance in self-regulation. The deformation degree of S3 and S4 are determined by the range of IBI oscillation which is closely influenced by participants' breathing regulation. The better they perform in deep breathing, the more regularly and smoothly the shape changes. Usually, it took a few deep breathes (20-30 seconds) to make S3 and S4 show an apparent shape change. We found that a few visitors did not seem to have enough patience to go through this gradual physiological process. This limited their ability to control the surface well and also hampered their experience during the interaction.

For those who had made the surfaces to show a desired shape-changing pattern, they suggested that the up-and-down motion and the bulge deformation of S3 was a very intuitive expression associated with human's breathing. Some participants suggested that the bulges on the surface during an inhale made them think of '*blowing a special balloon*' or an '*inflated lung*'. A few participants said that the shape changes of S3 helped them deepen their breathing. For instance, one participant stated that '*I think my breaths became smoother, and my breathe-out period became a little bit longer because I tried to make the surface flat*'. The participants thought S4 seemed more personated. They mentioned that the motion of the spiral parts looks like one's eyes rolling left and right, which made them easy to expect the motion of S4 responding to their position and movements. Compared to the up-down motion of S3, it seemed more difficult to associate the side-to-side motion of S4 with human breathing movement.

S3 and S4 suffered a similar problem caused by the jump-wire movements of the servomotor. It seemed hard to transform a series of discrete IBI data into a continuous movement of the servomotor. Although we used a moving window (of 3 heartbeats data) as a low-pass filter to average the data, at the beginning of the interaction, the discontinuity, and irregularity of the participants' IBI data often led to a 'jammed' movement of the motor, which tended to be perceived as '*stressed*' and '*stuck*'. This also diminished the elegance of LivingSurface's expressions. We think a possible solution might be exploiting a new mapping strategy. A shape-changing 'model' can be developed with a set of 'rules' for defining a specific motion for a surface. The bio-data are not directly linked to the parameters of the actuators, but to the parameters of the model. In other words, the bio-data are not to trigger or generate shape changes, but to modulate a pre-defined shape-changing motion. When no bio-data is fed in, the surface can still follow its rules to change the shape with a smooth movement. As far as we know, this idea has been explored in the field of auditory display, named as model-based sonification (Hermann et al. 2011). Recently, Feijs & Delbressine (2017) used interpolation to smoothen the movements of an IBI-based mechanical actuator.

5.6 Discussion & Conclusion

LivingSurface aimed to create a shape-changing interface that uses the qualities of physical change to enhance the user interaction with digital, physiological information. Since LivingSurface took heartbeat data as the input, we managed to design a novel HRV biofeedback, which could facilitate users to improve their HRV during a relaxation training. In the presentation mapping, we intentionally addressed the natural coupling between the expressive parameters of the surfaces and the human physiological activities, such as mapping the heartbeat to the vibration (S1) and the breathing to the bulges on the surface (S3).

We conclude this chapter with some prospects on the application of LivingSurface in biofeedback. The accuracy of S2 for information display is insufficient, but we think it can be an excellent 'accompaniment' in meditation, mindfulness and yoga practices. Its wind-driven shape changes represent one's breathing movement intuitively and naturally to encourage deep breathing. The wind produced by S2 could also stimulate the user's tactile sense. The good aesthetic qualities make S3 and S4 suitable as a decoration in office and home environments. We think they have the potential to be an ambient display to show a user's long-term HRV level for stress intervention. Also, S3 has better accuracy and natural dynamic expression. We think S3 can be used as a tangible interface of an HRV biofeedback system, assisting users in everyday relaxation training.

6

Breathe with Touch: Tactile Interface for Breathing Assistance

6.1 Introduction

The sense of touch enables us to interact with real objects around us, and meanwhile, to perceive these interactions. Hale & Stanney (2004) suggested that the bidirectional property of the touch sense provides a basis to enhance motor learning and somatic experience further. The study by Anon (2010) revealed that tactile feedback could reduce the perceived workload in learning tasks and enhance the user's feeling of presence. Moreover, stimulating the tactile sense might also give people relaxing experiences or emotional experiences that are beneficial for stress mitigation and health. As such, tactile stimuli are often used as a way to reduce physical stress and make people feel better, such as in massaging techniques and physiotherapy. Tactile feedback can also be integrated into a multimodal interface to enhance user experience. For instance, Dijk and Weffers (2011) developed a breathing guidance system to provide users with an immersive experience through a multimodal interface of auditory and vibrotactile stimuli.

Breathing techniques have been widely used for stress relief and relaxation (Gilbert 2003). A few deep breathes can quickly improve the autonomic balance and mitigate harmful effects of stress on our health. A regular breathing training can help people to improve their breathing skills and strengthen the physical capability to adapt to chronic stress. A variety of breathing training devices and APPs are developed for guiding users to achieve an optimal breathing pattern. In these systems, the breathing guidance is usually presented by graphic interfaces, as shown in Fig 6.1. In a new application, visual displays are often combined with

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This chapter is largely based on

Yu, B., Feijs, L., Funk, M., & Hu, J. (2015). Breathe with touch: a tactile interface for breathing assistance system. In *Human-Computer Interaction* (pp. 45-52). Springer, Cham.

an audio or haptic augment to improve the usability of the interface. For instance, the *Breathe* APP of *iWatch* combines an on-screen visual pattern with a rhythmic vibration to deliver breathing guidance, as shown in Fig 6.1(c). However, very little work has explored a shape-changing interface for tactile breathing guidance.

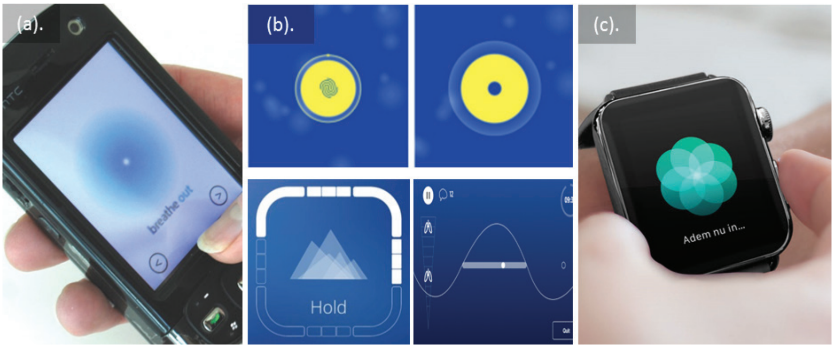

Fig 6.1
The GUIs in the breathing training products (a) Breathing guidance provided by smartphones (Morris et al. 2010) (b) Graphics interfaces for breathing guidance (c) Breathe App in iWatch

In this chapter, we present the design of Breathe with Touch (BwT) — a tactile interface that provides breathing guidance through a shape-changing airbag. The hand-sized airbag inflates and deflates to simulate the human deep breathing rhythm of 0.1Hz, so that the user can rest a hand on it and feel the changes as a type of breathing guidance. We aim to investigate whether the shape changes of BwT could be 'mirrored' by the users, leading them to a slow and smoothing breathing pattern. BwT was evaluated from three aspects: the effect on stress reduction, the efficacy of breathing guidance and the usability of the interface.

6.2 Design and Implementation

To design a proper tactile breathing guidance, we observe the nature of human breathing movement. People breathe with the fluctuation of the diaphragm between chest and abdomen. As an individual inhales, the diaphragm contracts and flattens, causing the expansion of lungs. Conversely, on an exhalation, the diaphragm relaxes and moves upward to reduce the space in the chest cavity (see Fig 6.2). Our lungs are like two air balloons inside the body. The shape changes of the lungs depend on the respiratory airflow. The concept of Breathe with Touch entails a tangible interface that simulates human breathing movements through the inflation and deflation of an airbag. As shown in Fig 6.2, a user can perform a breathing training with eyes closed and one hand resting on BwT. By touching, the user feels the guidance through the shape changes of the airbag. The natural coupling between human breathing movements and the interface's inflation-deflation actions aims to minimize the cognitive workload of users and facilitate their intuitive interpretation of the display. Besides, a slow movement of the airbag also aims to offer a tactile stimulus, helping the users to relax spontaneously. We assume that a slow inflation-deflation process of the airbag could render the digital breathing guidance into a tactile stimulus, which can be experienced as soothing and relaxing.

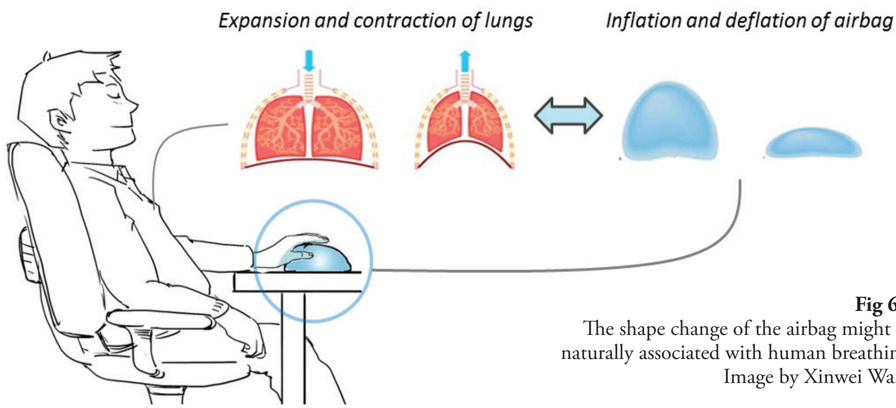

Fig 6.2
The shape change of the airbag might be naturally associated with human breathing. Image by Xinwei Wang

A hand-sized ellipsoid airbag was made of thermoplastic textile and covered by a layer of soft velvet. The maximum volume of the airbag is around 120ml that is the similar size of a computer mouse. This allows the users to identify the subtle shape changes easily by hand. The sensitive tactile feelings from the hand and fingers ensure that the users can perceive the guidance clearly. BwT presents the breathing guidance in the following way: when the airbag inflates, an inhale activity is implied. When the airbag deflates, an exhale activity is implied. An air pump and a solenoid valve implement the inflation and deflation of BwT. For the inflation, the air-pump pumps air into the airbag while the valve is closed. For the deflation, the air-pump stops working, and the valve opens. The user does not need to press intentionally, the hand on the airbag can push the air out gently with its weight.

According to the literature (Vaschillo et al. 2006), most people could achieve a high HRV level with a respiration rate at six cycles per minute (c/min). Here, BwT was implemented as a feed-forward system with a pre-set breathing guidance of six c/min. It starts from a deflated state then goes into an inflated state, then returns to the deflated state again. The duration of this inflation-deflation process is ten seconds. As shown in Fig 6.3(a), BwT can be embedded into a complete closed-loop IBI biofeedback system for a resonant breathing training.

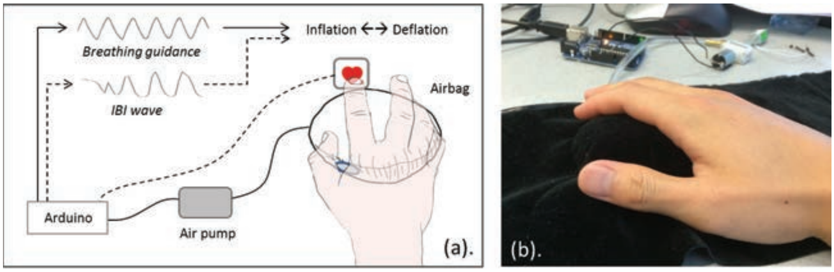

Fig 6.3
(a) The schematic diagram of Breathe with Touch system. (b) a user's right hand on the airbag

6.3 Study one: Evaluation of the Effects on Stress Reduction

We conducted the first user study to investigate whether BwT could facilitate deep breathing and improve heart rate variability effectively. 12 volunteers (six females and six males, age range: 19 to 24) participated in the study. Each participant performed an arithmetic test twice, once before and once after the breathing training with BwT. The arithmetic test is a fast-paced speed drill where the participants are given 10 minutes to solve as many arithmetic problems as they can. It aims to simulate a stressful condition. Heart rate variability (SDNN), respiration rate and the self-reports of State-Trait Anxiety Inventory (STAI-S) were measured in both pre-training and post-training tests. The differences were analyzed using a paired-samples t-test. A p-value of <0.05 was considered to be statistically significant.

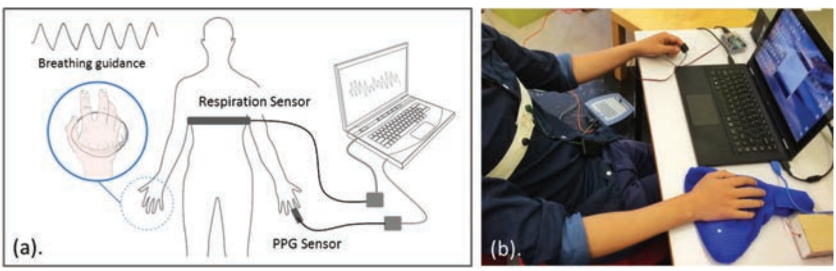

Fig 6.4
(a) The diagram shows the experiment set up (b) one participant performed breathing training with BwT

The experiment followed the procedure shown in Fig 6.5. On arrival at the laboratory, the participant was instructed how to use BwT for breathing training. A PPG sensor was worn on the left index finger. A respiratory sensor was placed at the abdominal level. Then the participant put on a noise-canceling headphone, sat quietly and relaxed for 5 minutes. After this resting period, the participant did the pre-training arithmetic test for 10 minutes. When completed, the participant filled out the STAI questionnaire immediately. After another 5-minute rest, the participant performed a 10-minute breathing training with BwT. The instructions were given as follows: "*Please follow the changes of the airbag to breathe. When the airbag inflates, you should breathe in. When airbag begins to deflate, you should breathe out. This session will last for 10 minutes.*" After the breathing training, the participant completed the post-training arithmetic test, and after that, filled out the STAI again.

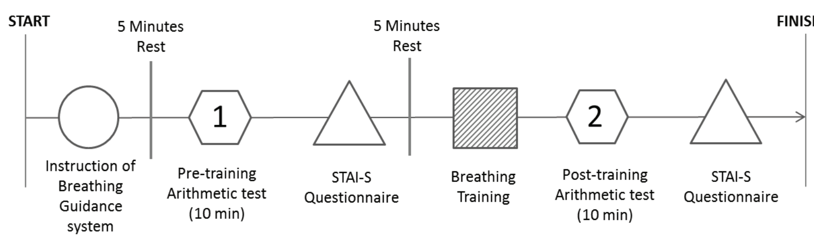

Fig 6.5
The experiment procedure

The physiological measurements were missing from two participants because of the sensor problems. As the index of HRV, SDNN was increased among all participants after the breathing training, as shown in Fig 6.6 (a). The SDNN of the post-training test was significantly higher than the pre-training test (49.5 ±14.2 *vs.* 66.3 ± 20.4; Pre-training vs. Post-training, $p<0.05$). Regarding the results of respiration data, seven participants showed a slower respiration rate during the post-training test. The difference between pre- and post-training tests was not significant (18±6 *vs.* 15±2 cycles; Pre-training *vs.* Post-training).

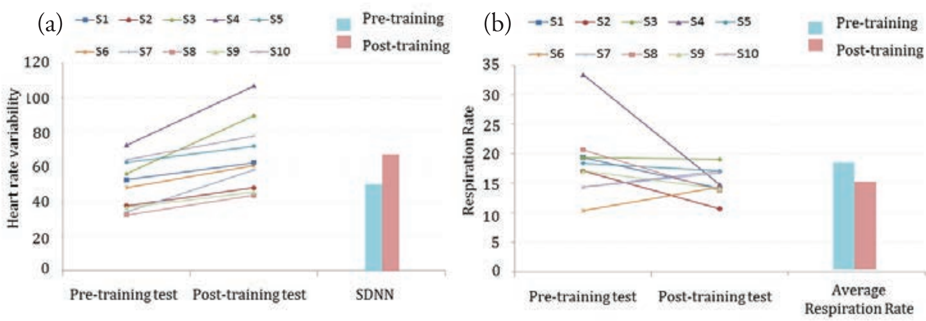

Fig 6.6 The HRV (SDNN) and respiration rate during the arithmetic tests before and after the breathing training

The results of the STAI-S questionnaire are shown in Fig 6.7. Nine participants reported a lower anxiety level during the post-training test. Three participants reported increased anxiety (participant #1, #4, and #5). The STAI-S scores were not significantly different between the two tests before and after the breathing training (46±11 *vs.* 39±9 points; Pre-training *vs.* Post-training).

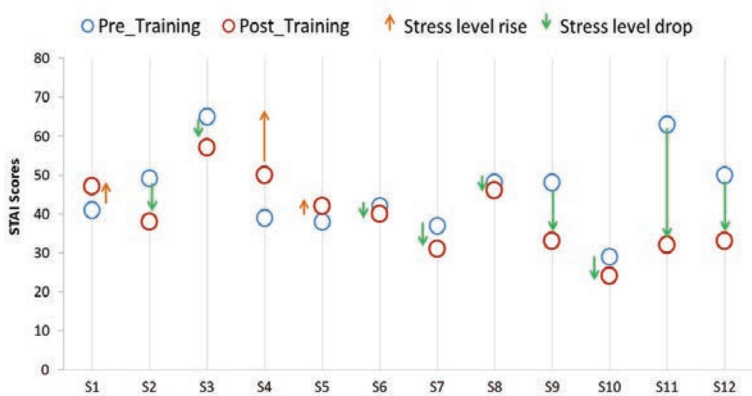

Fig 6.7 Scores of STAI-S before and after the breathing training with BwT (N=12)

6.4 Study two: Evaluation of Interface Usability

We conducted the second study to investigate the usability of BwT as a tangible interface for presenting breathing guidance. Ten participants (four females and six males, age range: 20 to 35) were recruited. All participants completed three 10-minute breathing training sessions with the same breathing guidance but presented in different sense modalities: visual, auditory and haptic. The experiment followed a within-subjects design with counter-balancing to avoid carry-over effects. As shown in Fig 6.8 (a), a visual and an auditory breathing guidance were designed for comparing with the tactile expression of BwT. The visual interface uses an ellipse with varying radius to represent breathing guidance. When the ellipse grows, an inhale process is implied. The auditory interface uses a sound with a changing volume to present breathing guidance. An increasing volume prompts users to breathe in, and a fading sound implies breathing out. The tactile interface of BwT presents the breathing guidance through the airbag's inflation and deflation. The interface usability was evaluated by using an adapted Lund's USE Questionnaire (Lund 2001). The questionnaire includes three dimensions: *Ease of use*, *Ease of learning* and *Satisfaction*. All the questions use a seven-point Likert scale (1=strongly disagree, 7=strongly agree). The differences between three interfaces were analyzed using a paired-samples t-test. A p-value of <0.05 was considered to be statistically significant.

Fig 6.8(b) shows the results of USE questionnaire. The tactile interface received the highest scores in three dimensions. Regarding *Ease of use* and *Ease of learning*, there were no significant differences between the tactile, auditory and visual interfaces. Regarding *Satisfaction*, the score of the visual interface was significantly lower than the tactile and auditory interfaces (15±3, 14±3 *vs.* 11±2; Tactile, Auditory *vs.* Visual, respectively, $p<0.05$). From the open-ended interview, we got more positive feedback about the tactile interface. The tactile guidance offers a more comfortable condition for breathing regulation. 7/10 participants chose the tactile interface as their favorite one. Specifically, they expressed a strong interest in relaxation with the tactile interface and emphasized that it was more comfortable due to the touch experience.

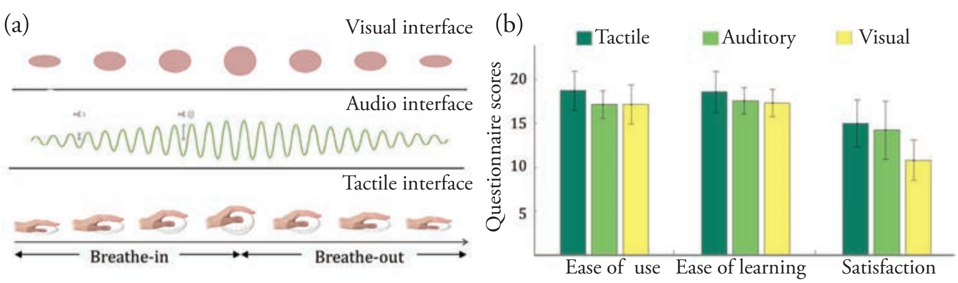

Fig 6.8 (a) The breathing guidance presented in different sensory modalities (b) the results of the interface usability

6.5 Discussion

In the previous chapter, we had already explored the natural coupling between the expressions of LivingSurface and the human physiological activities. Take an example of LivingSurface S3, when the users breathe in deeply; the cutout structures will curve and bulge outward, 'imitate' human breathing. In this chapter, a tangible interface, BwT, was designed to provide a tactile breathing guidance with an inflatable airbag. Different from LivingSurface, BwT focuses on touch sense, which may enhance the somatic experience. BwT embodies a natural coupling that can be perceived by touch. The results of study one show that a short-period of breathing training with BwT can reduce respiration rate and improve the HRV efficiently. Regarding the usability, a breathing regulation following the shape changes of BwT seemed more effortless and spontaneous. The high marks on *Ease of use* and *Ease of learning* suggest that BwT makes it easier for the users to adapt their breathing movements to an optimal pattern. The inflation and deflation of the airbag may elicit an instinctive and smooth transition between inhalation and exhalation. The high ratings on *Satisfaction* also show its potential in improving comfort and relaxation during the breathing training.

In the second study, most of the participants reported that BwT allowed them to perform breathing training with eyes closed and to better focus on their breathing with fewer distractions. However, they also reported a major limitation of BwT —it is too noisy. Most users prefer a quiet environment during relaxation training. Reducing the noise from air pumps or motors seems still a technical difficulty in a shape-changing biofeedback interface for relaxation training. The air pump used in our prototype is featured with low noise. However, still, the level of noise was undesirable so that we used a noise-canceling headphone in our experiments. We suggest an improved structural and model design for BwT to isolate the unpleasant noises. The tactile feedback can also be combined with an auditory display, where the sound and music can be used to mask the noises. Although we have not continued with the research on tactile biofeedback, we still believe that tactile biofeedback, especially addressing the natural coupling in the presentation mapping, has the potential for enhancing the somatic experience and offering a more pleasant and comfortable way for biofeedback-assisted relaxation training.

PART III

In this part, we explore using ambient media for biofeedback display. We assume that ambient displays with light and nature sounds may enhance user experience with biofeedback due to improved usability, accessibility, and comfort. In chapter 7 and 8, we present the design of an auditory biofeedback system based on nature sounds. In chapter 7, we conducted an experimental study to test the modulation of various nature sounds for calm information display. The study concluded with a simplified three-layer structure and a perceptual model of nature soundscape, which was used in the design of BioSoundscape presented in chapter 8. BioSoundscape harnesses various nature sounds to create a 'calm' soundscape that responds to the user's physiological activities and states. It can not only serve as an ambient audio display for biofeedback but also a natural augment to the indoor acoustic environment for relaxation. In chapter 9, we present DeLight, a lighting biofeedback system. In addition to presenting biofeedback data, ambient light was also used to offer a comforting environmental stimulus for relaxation training. In chapter 10, we integrated BioSoundscape and DeLight together into a room-scale audio-visual biofeedback system, RESonance, for immersive biofeedback training. In chapter 11, RESonance was applied to a multi-session biofeedback training with young soccer players and Ph.D. students. We evaluated its effectiveness in skill-learning for stress coping, and also investigated the users' learning curve with biofeedback.

7

A Model of Nature Soundscape for Calm Information Display

7.1 Introduction

7.1.1. Calm information display

The design of auditory displays has traditionally addressed the questions around how to present the information in a form that is easy to perceive and efficient to use. However, with the overwhelming amount of information coming to us in everyday life, another question has often been asked and discussed recently: how could the technologies calmly inform us without overburdening us? The increasing bandwidth and enriching channels of information progressively engage our attention and keep us farther away from the sense of calmness. Therefore, besides the effectiveness of information delivery, increasing efforts are being made to facilitate the user's calmness with information. Calm Technology was formulated by Mark Weiser & John Seely Brown (1997). It suggests that the information display should "*engage both the center and the periphery of the user's attention, and in fact moves back and forth between the two.*" A 'calm' auditory display can shift the information from the user's focus of attention to the auditory periphery, and the users can attune to the information without explicitly attending to it. This idea of calm technology inspires this chapter. We intend to develop a model of nature soundscape which can be interfaced with a biofeedback system, and present the physiological information calmly in an everyday environment.

7.1.2. Model-based sonification

In auditory displays, the sonification approach plays a critical role in transforming the data into the right form of audio signal or coupling the data with the auditory

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This chapter is largely based on

Yu, B., Hu, J., Funk, M. and Feijs, L., (2017). A Model of Nature Soundscape for Calm Information Display. *Interacting with Computers*, 29(6), pp.813-823.

content. According to Hermann & Ritter (1999), five sonification approaches are mainly used for auditory display: Audification, Auditory icons, Earcons, Parameter-Mapping (PM), and Model-based sonification (MBS). Audification transforms the data directly into the audible domain, where a time series directly controls the audio signal amplitude (Sandell 1996). The term 'Auditory icons' was coined by Gaver (1986) and has been embodied in several designs of his, such as the SonicFinder (Gaver 1989), SharedARK and ARKola bottling plant (Gaver et al. 1991). Auditory icons exploit everyday sounds to convey information in human-computer interaction. The semantic link between the attributes of everyday sound-producing events and attributes of computer events makes the auditory icons less annoying and easier to be learned by the users. Earcons (Blattner et al. 1989) are using synthesized tones or sound patterns as audio messages to represent specific events and convey information. Compared to Auditory icons, Earcons are more abstract and often used in combination with other earcons to produce a compound audio message. Earcons are not only designed for interacting with computers but used more widely with a long history, such as alert signals from emergency broadcast systems. The users may need a longer learning process to build the relationship between the Earcons and their represented meanings.

In those interactive systems that communicate high-dimensional data, Parameter-Mapping (PM) is a more common approach to convey information or perceptualize data (Hermann, 2008). In PM sonification, the data values are directly mapped to the acoustic attributes of a sound, such as the duration, pitch, loudness, position, and brightness. In other words, the data 'play' an 'instrument' by manipulating the parameters of a synthesizer. One of the advantages of PM is multivariate representation. Different data variables can be mapped to different acoustic parameters concurrently to produce a complex sound. Thus, many data dimensions can be listened to at the same time. However, because the sound pattern is associated with the data structure, the sounds that are produced by PM might often be unpleasant. It is also difficult to predict the user's perception of the data-controlled sounds produced by a multivariate PM. These problems were reported in (Smith et al. 1994) and indicated by (Barrass & Kramer, 1999; Hermann, 2008).

In our previous explorations (chapter 3), four auditory HRV displays were created based on PM approach. The IBI data were directly mapped to the rhythmic variations in MIDI notes. The results of the user study showed that the created auditory displays could be useful as an alternative to the graphic display of IBI tachogram. However, regarding user experience, those audio forms received a low score on the '*comfort of use*.' Some users even reported more anxiety with the audio displays. We found that the PM-based sonification can be effective in transforming the HRV data into the sounds but still challenging to shape a relaxing and pleasant user experience with auditory biofeedback.

Model-based sonification (MBS) was introduced by Hermann & Ritter in 1999. It employs more complex mediation between data and sound by introducing a virtual 'sound-generating model,' whose properties are linked to the data source. The sonification model acts as a 'virtual instrument,' whose 'material structure' defines the sound properties and 'underlying physics' defines the modulation of the output sounds. MBS is commonly designed to enhance user interaction, which involves "interacting with data-driven virtual acoustic objects" (Hunt et al. 2004). For instance, a virtual sound object (VSO) was developed and could be 'played' by the movements of the upper limbs for biofeedback rehabilitation (Maes et al. 2010). In this chapter, we follow the approach of model-based sonification and focus on building a controllable 'virtual natural environment' as a sonification model.

7.1.3. Auditory display with nature sounds

Besides being coupled with the data for information display, the audio content or audio signal itself can be an auditory stimulus contributing to the user experience during human-computer interaction. For instance, a piece of music may induce autonomic relaxation, but a short high-pitched tone within this piece may cause an alert adversely. Music signal can stimulate the imagination (Lundqvist et al. 2009) and boost moods (McCraty et al. 1998). Nature sounds can also powerfully induce positive emotional states (Ulrich et al. 1991), help in calming down (Alvarsson et al. 2010; DeLoach et al. 2015) and sustain the attention (Kaplan 1995).

In addition to fostering the experience of calmness and relaxation, nature sounds have another advantage for auditory display as they are intuitive, familiar and may be understood quickly and learned easily. Nature sounds are among 'everyday sounds' around us. When we are outdoors in a garden or the woods, we hear the sounds of birds whistling. It does not usually take too much for us to adapt to these sounds. As such, nature sounds are often used in ambient displays and peripheral interactions by creating a 'calm' sonic environment, which can engage the periphery of our attention to receive the presented information. For instance, Eggen & Van Mensvoort (2009) used bird sounds in a peripheral display to communicate information about the activities in the office. AmbientROOM (Ishii et al. 1998) modulated the volume and density of bird and rainfall sound to present the number of unread email messages and the value of a stock portfolio. Audio Aura (Mynatt et al. 1997) used seagull cries and beach birds as auditory cues to provide office workers with relevant information such as the availability of colleagues.

The value of everyday sounds used as Auditory icons lies in their associated meanings. In the above studies (Eggen & Van Mensvoort 2009; Ishii et al. 1998; Mynatt et al. 1997), the nature sounds were used individually as a particular type of earcons, like musical tones. They have been given a renewed meaning in specific contexts to communicate the targeted information, such as the number of unread email messages by the volume and density of birds (Ishii et al. 1998). The changes of an individual nature sound seem to be meaningless to us, but the changes of the soundscape shaped by multiple changing nature sounds can inform us through our intuitive perception of the immersed acoustic environment, such as loudness, eventfulness, richness, calmness, and pleasantness. In the view of model-based sonification, a nature soundscape can be modeled, and the perceptual and emotional attributes of the model can be used to present information in a peripheral and intuitive way.

7.1.4. Our intention

In this chapter, we follow the idea of model-based sonification and propose a nature soundscape model for calm information display. Different from the other sonification models focusing on the design of a 'virtual instrument', the nature soundscape (NS) model is developed as a 'virtual natural environment.' The developed NS model may offer a framework to create a coherent soundscape, but also a means to present information by linking data to the attributes of a nature soundscape. This chapter is divided into two parts: firstly, designing the 'structure' of nature soundscape and secondly establishing the 'underlying relations' between the acoustic parameters of individual nature sounds (interfacing with data) and the listener's perception of the whole nature soundscape (interfacing with a human).

7.2 Constructing a Nature Soundscape

According to Schafer Murray (1993), the 'soundscape' refers to the unique experience of inhabiting an acoustic environment with emphasis on the individual's sensation and perception of different types of sounds. Since then, the term 'soundscape' has been used extensively to describe an 'acoustic environment' about the acoustic resources within a given area. Nature soundscapes have been studied in many fields, ranging from urban design (Yang & Kang 2005), monitoring of the wildlife (Pijanowski et al. 2011) and auditory display in public space (Eggen & Van Mensvoort, 2009). A central topic spanning across these fields is the informational aspect of the soundscape, either extracting information from a recorded soundscape or conveying information by creating a new one. In this chapter, we focus on the latter.

A nature soundscape may refer to both an acoustic environment consisting of various nature sounds and also the listener's perception and experience of sounds heard as an environment. A nature soundscape may consist of various sounds including animal vocalizations, the sounds of weather and other natural elements. As each sound element can be a possible information carrier, a nature soundscape can present multi-channel information simultaneously. For instance, Hermann, Drees, & Ritter (2003) combined the sounds of wind, rainfall, thunder and frogs as an auditory weather forecast to present various channels of weather information. Moreover, a rich diversity of nature sounds in a coherent context may also create an acoustic environment which can be experienced to be pleasant, calm, and relaxing.

7.2.1 Structure of nature soundscape

The nature soundscape that arises from a real natural space tends to be very complicated, varying spatially and temporally with much diversity in sounds and their distribution. It is difficult to directly exploit a real recording of the natural environment for information display. Therefore, instead of the realism of the synthesized soundscape, we focus on building a controllable 'virtual natural environment' with limited sound components and investigating the human perception on its overall attributes.

According to Pijanowski et al., (2011), our working definition of a nature soundscape is "*the collection of biological and geophysical sounds that emanate from a natural environment.*" Thus the nature soundscape in this chapter does not include the 'anthrophony' caused by humans, only focuses on the 'biophony' and 'geophony' created by nature including biology and geography. According to Krause (1987), 'biophony' describes the composition of sounds created by organisms and 'geophony' describes non-biological ambient sounds occurring at a site. Based on the studies of Murray (1993), the sound components in a soundscape can be classified into three types: keynotes, signals, and soundmarks. The keynote sound is the tonal center of a soundscape such as the sound of the running water by a riverside. The signals sound is the informational sounds that appear infrequently and separately. A soundmark is a unique sound to an area, like an audible landmark.

Table 7.1
The parameters and perceptual attributes in the three-layer structure of the nature soundscape

	Sound layer	**Classes of sounds**	**Sound Source**	**Audio Signal**	**Parameters**	**Example**
Cs	climatic sound	Ambience noise	single	continuous	volume	wind
Gs	geophysical sound	Keynote sound	single	continuous	volume	water stream
Bs	biological sound	Signals sound	multiple	discrete	volume; density; type variation; rhythm variation; direction variation	silvereye, wren, greenfinch, collared dove, cuckoo

Here, we simplify the composition of a nature soundscape as a three-layer structure, consisting of geophysical sounds (Gs), biological sounds (Bs) and climatic sounds (Cs), see Table 7.1. Geophysical sound (Gs) reflects the geographical features at a site. It serves as the keynote sound, which shapes the basic scenario of a nature soundscape. Biological sounds (Bs) serve as signal sounds, reflecting natural events and processes. It may consist of a diverse array of nature sounds produced by mammals, birds, amphibians, and insects. A soundscape can also be described regarding Hi-Fi and Lo-Fi based on the ambience noise level (Schafer Murray 1993). In Hi-Fi soundscapes, discrete sounds can be heard apparently because of low ambience noise level. In Lo-Fi soundscapes, all the sounds are very compact and obscured by the high level of ambience noise. We consider the ambience noise as an independent component, which influences the perception of the soundscape regarding the Hi-Fi and Lo-Fi. Thus, climatic sound (Cs) refers to the ambience noise created by the climate such as the wind, rain, or shore noise. This simplified structure helps in selecting different nature sounds and mixing them as a whole. The resulting soundscape can be one of the many instantiations of the class of 'nature soundscape'. For example, in our experiment, a sample soundscape of 'forest' was developed with the combination of the wind (Cs), water stream (Gs), and bird songs (Bs).

7.2.2 Parameters of nature soundscape

According to Pijanowski et al., (2011), a soundscape possesses four measurable properties: acoustic composition, temporal pattern, spatial location, and acoustic interactions. These properties are usually measured and analyzed for getting information about a soundscape ecology. In this chapter, we do the reverse that we select the controllable acoustic parameters based on these properties. The acoustic interactions in a nature soundscape may vary widely according to animal activities. For practical reasons, we only address the componential, temporal, and spatial properties. The composition of NS is associated with various acoustic parameters including frequency, amplitude, and type of nature sounds. The temporal pattern of NS is mainly reflected by specific biological events. The spatial location refers to the direction and distance of the sound source.

Based on the above structure, in a nature soundscape, the sound selected for the Cs layer is a type of natural white noise, which is continuous and from a single source. In the Gs layer, only one geophysical sound will be selected as the keynote sound, and it is from a fixed sound source. Therefore, for both Cs and Gs layers, the volume is the only acoustic parameter to be adjusted. The Bs layer is comprised of various biological sounds from multiple moveable sources, such as birds, frogs, and insects in the forest. Different from Cs and Gs, the sounds in the Bs layer are discrete, and the sources might be moving around. Therefore, more parameters regarding the temporal patterns and spatial location properties are selected.

For the Bs layer, besides the volume, the second parameter is density, which determines the basic time interval between two successive sound playings. A higher density shortens the time interval between the Bs sounds. The other three parameters of the Bs layer are mainly about the dynamics of the Bs sounds; they are the variations of sound type, rhythm, and direction. The type variation determines how many types of the biological sounds will be 'activated' for playing. A higher type variation means that, for each playing, the sound source will be selected from a wider range of 'sound library'; with the same density, more types of Bs sound will occur in the soundscape. The rhythm variation is the range of variation in the basic time interval which is determined by the parameter of density. A higher rhythm variation means that the Bs sounds will occur more unevenly, with more flexibility. All Bs sounds can be played through mono or stereo channels, which create directionality, perspective, and space. The direction variation determines the proportion of the Bs sounds presented through the stereo left or right channels. A bigger direction variation will lead to a better stereo-surround quality.

In summary, we propose seven parameters distributed in different layers: Cs-volume, Gs-volume, Bs-volume, Bs-density, Bs-rhythm variation, Bs-direction variation and Bs-types variation. We assume that by controlling one or more of these parameters, the listener's overall perception of the soundscape will be influenced.

7.2.3 Attributes of nature soundscape

The listener's perception of multiple mixed sounds in a coherent context may create the sensation of experiencing a particular acoustic environment. Many studies have been conducted to assess and understand the perception of soundscapes (Coensel & Botteldooren 2006; Raimbault et al. 2003). In these studies, the assessment of a soundscape involves more perceptual and emotional measures rather than just identification and description of the sound sources. Various attributes of soundscapes emerged in the assessments, such as pleasantness, loudness, eventfulness, familiarity and sound dynamics. Coensel & Botteldooren (2006) suggested that the calmness and pleasantness might be a result of multiple other attributes such as loudness, eventfulness, familiarity, the dynamics of the sounds, and the factors related to the spatial characteristics and the spectrum or timbre of the soundscape.

Table 7.2 the selected perceptual attributes of the nature soundscape

	Perceptual attributes	Rating Scales
1	Loudness	*quiet (1) vs. loud (5)*
2	Richness	*deserted (1) vs. lively (5)*
3	Steadiness	*unsteady (1) vs. steady (5)*
4	Spatial Impression	*closed (1) vs. open (5)*
5	Naturalness	*artificial (1) vs. natural (5)*
6	Calmness	*irritating (1) vs. calming (5)*
7	Pleasantness	*unpleasant (1) vs. pleasant (5)*

A nature soundscape is normally assessed by using a semantic differential. Table 7.2 shows the seven perceptual attributes that are most commonly used to describe the perception of a nature soundscape. Based on the results from De Coensel & Botteldooren (2006) and Raimbault et al. (2003), loudness is the most important attribute which is about the strength of a soundscape. The attribute of richness describes sound diversity in a soundscape. Next, the attributes of steadiness and spatial impression are related to sound dynamics regarding the temporal balance and the spatial localization. The naturalness evaluates the realism of a nature soundscape. The calmness and pleasantness are selected to assess the appreciation and user experience towards a soundscape. In this chapter, a specific rating scale was designed with seven questions for evaluating the listener's perception of the nature soundscape.

7.3 User Experiment

A user experiment was conducted to understand the relationships between the acoustic parameters and the user perceptions of the nature soundscape. Based on the proposed NS structure, we created a soundscape of 'forest' to investigate how we can influence the user perception of the soundscape through the modulation of its acoustic parameters. By setting each of seven acoustic parameters into three levels, 21 soundscape samples were created. In a within-subjects experiment, each participant was exposed to all soundscape samples and completed the soundscape rating scale for each sample. The independent variable is the level of the parameters (low, moderate and high), and the dependent variables are seven perceptual attributes of the soundscape measured by the rating scales.

7.3.1 Participants

Twenty participants took part in the experiment through informed consent procedures. All participants were volunteers. They were randomly selected from a variety of undergraduate and graduate classes. The eleven males and nine females ranged in age from 22 to 33. All participants reported no history of diagnosed hearing impairments. Participants who were trained listeners, either through professional audio training or music education were excluded from the experiment. The participants were unaware of the specific aims of the experiment, the modulation and the predicted effects of the different samples.

Table 7.3 Details of parameter setting for creating the samples for the experiments

Layers	Sound selection	Parameters	Parameters level		
			Low	Moderate	High
Cs	Wind	Volume	0 dB	5 dB	10 dB
Gs	Water	Volume	0 dB	5 dB	10 dB
Bs	Birds	Volume	0 dB	5 dB	10 dB
		Density	10 sounds/min	20 sounds/min	30 sounds/min
		Type variation	1 types	3 types	5 types
		Rhythm variation	±0%	±20%	±40%
		Direction variation	100% Mono	50% Mono 50% Stereo	100% Stereo

7.3.2 Nature soundscape samples

Based on the results of our previous user survey (Yu, Hu, Funk, & Feijs, 2016), 'forest' is one of the most pleasant nature themes among the other scenes, such as ocean and grasslands. The moderate complexity also makes the 'forest' soundscape malleable and controllable. Therefore, we selected the nature sounds from the forest as the auditory contents for constructing the soundscape in this experiment. After analyzing the recorded soundscapes of the real forest, we created the soundscape consisting of wind sound as the climatic sound (Cs), a water stream for geophysical sound (Gs), and several types of birds (i.e., silvereye, wren, greenfinch, collared dove and cuckoo) for biological sounds (Bs). These bird sounds were selected as they are rated as the most likely to help people relax and recover from mental fatigue (Ratcliffe et al. 2013). Seven groups of soundscape samples are created with the same audio contents. Within each group, one acoustic parameter is modulated into different levels while other parameters are set to the default value (moderate level), see the Table 7.3. The volume of audio sources is normalized first and then amplified to different decibel values with audio software *Audacity*.

7.3.3 Procedure

All participants completed the experiment individually in a small testing room furnished with a recliner chair, rug, lamps, and audio equipment. All sound samples were played through acoustic noise-canceling headphones (*Bose, QuietComfort 25*). The participant was seated in the recliner with comfort and read the instruction before the experiment. Each participant listened to seven groups of soundscape samples in a randomized order. For each group, the order of samples was also randomized. The researcher started to play the samples one after another in the first group. After listening to each sample, the participant was asked to judge upon the attributes of what they hear with a rating scale. After each one group had been completed, the participants had 15 seconds to finalize their answers and hear a 30-second piece of music as a wash-out period.

7.4. Results

7.4.1 The rating scale on attributes of soundscape within each group

A repeated measures ANOVA was conducted to compare the collected ratings between the soundscapes with different parameter level. A p-value of <0.05 was considered to be statistically significant. Fig 7.1 shows the influence of each acoustic parameter on the user perception of the soundscape. Fig 7.1(a, b, c) shows the participants' ratings on the NS attributes with different levels of Cs, Gs, and Bs volume. As shown in Fig 7.1(a), with a high Cs volume, the NS is perceived to be significantly louder than the one with the low and moderate Cs volume. The pleasantness and calmness of the NS are reversed. In the second group, the loudness of the NS with high Gs volume is significantly higher than the one with moderate Gs volume. The loudness of the NS with moderate Gs volume is significantly higher than the one with the low volume. The other attributes like steadiness, spatial impression, naturalness, pleasantness, and calmness are all reversed.

Fig 7.1(c) shows that a high Bs volume also leads to a significantly higher rating on the loudness. Conversely, the spatial impression, naturalness, pleasantness, and calmness significantly decrease when the Bs volume is high. As shown in Fig 7.1(d), with a high density of Bs, the loudness, and the richness of the soundscape are significantly higher than the ones with a moderate and low Bs density. The pleasantness and calmness of the soundscape show opposite results. As shown

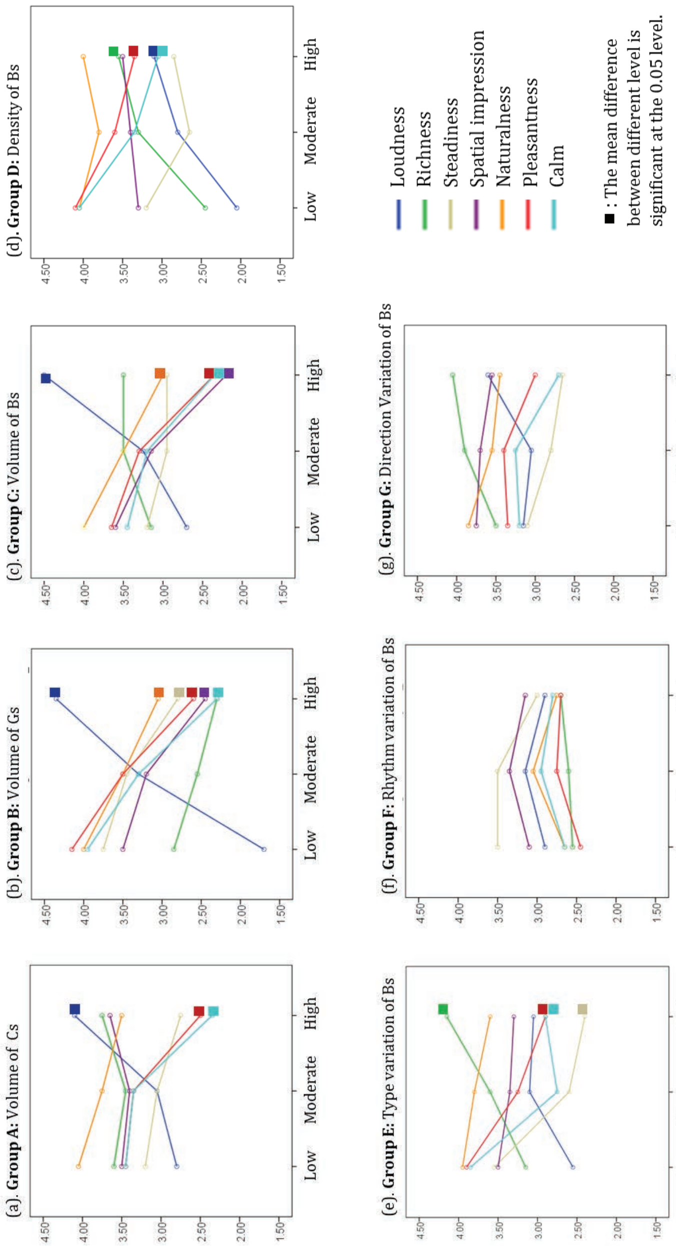

Fig 7.1
The rating scale on attributes of soundscape within each group with different parameter levels

in Fig 7.1(e), a high variation of Bs type leads to a significantly higher richness, but a lower steadiness, pleasantness, and calmness of the soundscape. Fig 7.1(f) and 7.1(g) show that the listener's perception of the nature soundscape was not changed significantly with different levels of rhythm variation and direction variation.

7.4.2 The correlations between acoustic parameters and perceptual attributes

A Pearson correlation coefficient was computed to assess the relationship between the acoustic parameter and perceptual attributes of the soundscape. Table 7.4 shows the results of correlation analysis between acoustic parameters and perceptual attributes. Regarding the loudness, there is a strong positive correlation between the loudness and Gs volume (r=0.854, p≤.001). There is a moderate positive correlation between the loudness and Cs volume (r=0.545, p≤.001) and Bs volume (r=0.677, p≤.001). There is a weak positive correlation between the loudness and Bs density (r= 0.453, p≤.001). Regarding the richness, there is a weak positive correlation between the richness and density of Bs layer (r=0.406, p≤.001), and type variation of Bs layer (r=0.384, p=.002).

Regarding the steadiness, there is a weak negative correlation between the steadiness and Gs volume (r=−0.372, p=.003), and type variation of Bs layer (r=−0.398, p=.002). Regarding the spatial impression, there is a weak negative correlation between the spatial impression and Gs volume (r=−0.365, p=.004) and Bs volume (r=−0.431, p=.001). Regarding the naturalness, there is a weak negative correlation between the naturalness and Gs volume (r=−0.357, p=.005). The calmness is negatively correlated with Cs volume (r=−0.408, p≤ .001), Gs volume (r=−0.647, p≤.001), Bs volume (r=−0.425, p=.001), Bs density (r=−0.461, p≤.001), and type variation of Bs layer (r=−0.375, p=.003). The pleasantness is negatively correlated with Cs volume (r=−0.404, p≤.001), Gs volume (r=−0.601, p≤.001), Bs volume (r=−0.445, p≤.001), Bs density (r=−0.346, p≤.001), type variation of Bs layer (r=−0.409, p=.001).

Table 7.4 The correlations between the acoustic parameters and perceptual attributes of nature soundscape

Layers	**Parameters**	**Perceptual Attributes**						
		Loudness	***Richness***	***Steadiness***	***Spatial Impression***	***Naturalness***	***Calmness***	***Pleasantness***
Cs	Volume	r=0.545 p≤0.001	r=0.071 p=0.589	r=−0.184 p=0.16	r=0.055 p=0.678	r=−0.201 p=0.123	r=−0.408 p≤0.001	r=−0.404 p≤0.001
Gs	Volume	r=0.854 p≤0.001	r=−0.254 p=0.05	r=−0.372 p=0.003	r=−0.365 p=0.004	r=−0.357 p=0.005	r=−0.647 p≤0.001	r=−0.601 p≤0.001
Bs	Volume	r=0.677 p≤0.001	r=0.138 p=0.292	r=−0.106 p=0.421	r=−0.431 p=0.001	r=−0.313 p=0.015	r=−0.425 p≤0.001	r=−0.445 p≤0.001
	Density	r=0.453 p≤0.001	r=0.406 p≤0.001	r=−0.139 p=0.29	r=0.079 p=0.549	r=−0.025 p=0.847	r=−0.461 p≤0.001	r=−0.346 p=0.007
	Type variation	r=0.225 p=0.084	r=0.384 p=0.002	r=−0.398 p=0.002	r=−0.075 p=0.566	r=−0.134 p=0.307	r=−0.375 p≤0.003	r=−0.409 p≤0.001
	Rhythm variation	r=0 p=1	r=0.058 p=0.658	r=−0.175 p=0.18	r=0.020 p=0.880	r=−0.030 p=0.820	r=−0.065 p=0.623	r=−0.114 p=0.385
	Direction variation	r=0.206 p=0.114	r=0.244 p=0.061	r=−0.181 p=0.166	r=−0.076 p=0.564	r=−0.147 p=0.263	r=−0.231 p=0.076	r=−0.172 p=0.188

7.4.3 The Nature Soundscape Model

Table 7.5 illustrates the relationships between the acoustic parameters and the perceptual attributes as a model. The model is built with the three-layer NS structure, which guided us to construct the nature soundscape samples. All perceptual attributes show a hybrid relationship with multiple parameters across the layers. Only the first five parameters show a correlation with the user perceptions of the nature soundscape. For the Cs and Gs layers, the volume is the only parameter to control, and for the Bs layer, there are three parameters: volume, density and type variations. As shown in Fig 7.2, these acoustic parameters can be regarded as the input of the model, interfacing with the dataset. Seven attributes of the soundscape are viewed as the outputs interfacing to the listener's perceptions and experience.

Table 7.5 The resulting nature soundscape mode

Layers	Parameters	Perceptual Attributes						
		Loudness	*Richness*	*Steadiness*	*Spatial Impression*	*Naturalness*	*Calmness*	*Pleasantness*
Cs	*Volume*	++					–	–
Gs	*Volume*	+++		–	–	–	– –	– –
Bs	*Volume*	++			–	–	–	–
	Density	+	+				–	–
	Type variation		+	–			–	–

\+ Positive, - Negative; +++/- - - Strong ; ++/- - Moderate; +/- Weak

We can conclude that, for the nature soundscape developed with the NS structure, there is evidence that the loudness is strongly related to the volume of three sound layers and the density of Bs sounds. The richness is related to the density and type variations of bio-sounds. The steadiness is related to the volume of Gs layer and density and type variations of bio-sounds. The spatial impression and naturalness are related to the volume of Bs and Gs layer. The calmness and pleasantness are related to all five parameters in the model.

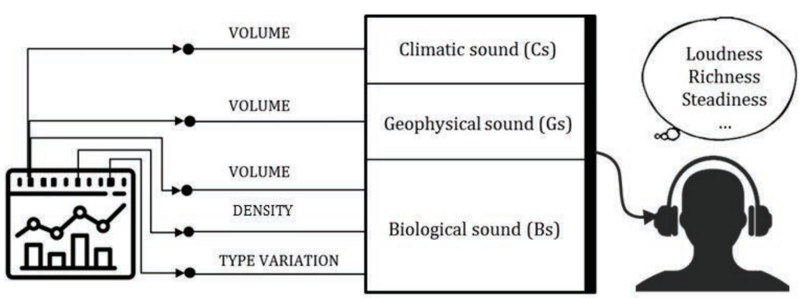

Fig 7.2 The NS model links the input dataset to the listener's perceptions and experience

7.5. Discussion

In our view, nature sounds can both inform and create calmness. Firstly, nature sounds can support calm technology with their subtleness and naturalness. Calm technology (Mark Weiser & John Seely Brown 1997) aims to maintain the user's awareness of the displayed information without overburdening. Like other everyday sounds, nature sounds are intuitive, familiar and tend to engage the periphery of people's attention. Nature soundscapes can create ambient awareness. For example, nature soundscapes can be applied to ambient displays in public space. The man-made nature soundscape is mixed with the real indoor soundscape, and the nature sounds could respond to the input data source or adapt to the inhabitants in the space. The inhabitants can be aware of the information through general feelings toward the acoustic environment without taking them out of their environment or task. The slow changes in the perceptual attributes of soundscape require a small amount of attention. The NS-model based interface is suitable to communicate status. The richness and steadiness of the nature soundscape can be manipulated to present some slow-changing status information, such as the temperature of CPU or the stress level of an office worker.

Secondly, nature sounds can be a desirable audio content to enhance the user's calmness and relaxation with the interfaces, especially in the applications for rehabilitation, stress management, relaxation training, and healthcare. Most nature sounds are pleasant and have a therapeutic effect due to their ability to foster the experience of calmness and relaxation. In previous studies (Eggen & Van Mensvoort 2009; Ishii et al. 1998; Mynatt et al. 1997), auditory displays were created with nature sounds by using Auditory icons and parameter-mapping, in which the data was directly linked to the parameters of the individual sounds. These audio displays are effective in information delivery, but few of them focused on creating a 'calm' soundscape. The developed NS model helps to select and organize the audio content within a nature theme, and provides a means to link the input data with the listener's perception on the soundscape for information display, as shown in Fig 7.2. Besides, the model may also suggest a mapping design by which the different nature sounds can be manipulated in a way that the audio output from the interface can be perceived as a calm and pleasant soundscape.

As suggested by (Blattner et al. 1989; Eggen 2016; Gaver 1993), people can perceive the sounds at different levels. Beyond a basic-level auditory event, people can also hear more complex, structured combinations of the individual events and perceive these combinations as the overall attributes or characteristics of the environment. Model-based sonification provides a possibility to 'edit' these attributes at higher semantical levels as stressed by (Hermann & Hunt 2005). The sound perception at different levels allows the audio display to move easily between the periphery and the center of our attention. The NS model was developed to link the data to the overall attributes of the soundscape, which makes it possible to manipulate the auditory display at 'perceptual' or 'experiential' levels. We anticipate an auditory display with which the listener can extract information by holistically listening to the nature soundscape, and also zoom in into a specific sound for more detailed information. In an NS model based auditory display, individual sounds can be chosen to be 'expressive' and 'functional' by retaining a close mapping between data and specific acoustic parameters. For instance, a specific type of bird sound (e.g., cuckoo) can indicate a discrete data event (e.g., an outlier), and the volume of wind sound can represent a continuous flow of data. These detailed sounds communicate explicitly in the center attention of the listener. Moreover, the data can also control several sounds jointly to shape the soundscape perceptually to be discriminable and inform the listener calmly in the periphery, for example, the richness of the whole soundscape conveys some supplementary information.

7.6. Conclusion

In this chapter, we propose a nature soundscape model linking between the acoustic parameters of individual nature sounds and the perceptual attributes of the whole soundscape. The correlations between the acoustic parameters and the human perception of the nature soundscape can be used as an interface between the data and specific information in different context. The NS model offers the designers and practitioners a new tool to utilize nature sounds in the design of auditory displays, which could support the calm technology and enhance the user experience. NS-model-based sonification offers new means for ambient displays, in which data could be used to drive an adaptive acoustic environment.

The nature soundscape model may provide the foundation for the further design of ambient auditory biofeedback with the nature sounds. Fig 7.3 shows an envisioned scenario where the wearable biosensors sense the physiological activities of a user and the ambient biofeedback system tunes the augmented nature soundscape in a home environment. The user may receive the biofeedback information by intuitive perception of the indoor acoustic environment soundscape. In the next chapter, we try to put this idea into practice. The NS-model is used in a new auditory interface named BioSoundscape.

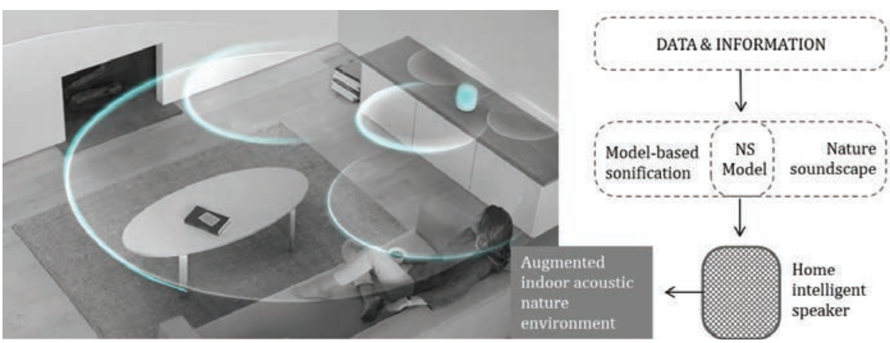

Fig 7.3 An envisioned scenario of ambient auditory biofeedback. Senses the physiological data and tunes the augmented nature soundscape at home environment for stress management and relaxation training

8

BioSoundscape: Biofeedback through a Nature Soundscape

8.1 Introduction

Auditory interfaces are quite common in biofeedback systems. Not only are they capable of presenting biofeedback data, but also they can induce calmness and relaxation by the audio signal itself. According to our systematic review described in chapter 2, auditory interfaces (including audio tones and musical expressions) account for around 25% of the biofeedback presentations. Based on different biofeedback data and application contexts, auditory biofeedback may vary from a pure tone to a piece of complex music. For instance, Tsubouchi & Suzuki (2010) developed a wearable device named *bioTones*, which converts EMG (electromyography) signal into a sound signal by pitch, loudness, and timbre mapping. Vidyarthi et al. (2012) created an ambient sound environment which responds to the user's respiration.

For promoting relaxation, musical biofeedback interfaces have been investigated widely. Harris et al. (2014) developed a musical biofeedback system that encourages slow breathing by adjusting the quality of music in proportion to the user's respiration rate. Bergstrom et al. (2014) designed a musical interface which presents the user's physiological state by adjusting the tempo and volume of music. Yokoyama et al. (2002) developed a heart rate biofeedback system which modulates the pitch and tempo of sound according to the user's instantaneous heart rate. Besides, in chapter 3, we have also explored the auditory biofeedback by directly mapping the heart rate variations to the rhythmic variations in MIDI notes (Yu et al. 2015). As we can see, the output of an auditory biofeedback system may take various forms including a pure tone, a chord, an ambient soundscape, or musical pieces. Despite these diverse audio forms, very little work has explored the feasibility and effects of nature sounds for biofeedback display.

Nature sounds, such as the birds singing and the murmur of a brook, can comfort an individual's mind and foster the experience of calmness and relaxation (Benfield et al. 2014; Alvarsson et al. 2010). Nature sounds have a wholesome effect on our health, helping us to fall asleep, focus at work (DeLoach et al.

2015), fight stress (Benfield et al. 2014) and boost moods. 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 (Alvarsson et al. 2010). Moreover, a mixture of sounds from a fountain and tweeting birds have also demonstrated stress-relieving effect via the autonomic nervous system (Benfield et al. 2014). In the field of HCI, nature sounds have been used for auditory display in various interactive systems (Bakker et al. 2010; Eggen & Van Mensvoort 2009; Ishii et al. 1998; Mynatt et al. 1997; Hermann et al. 2003) as alerts, notifications, warnings, status indication, or as the feedback to support interaction. We think that a nature soundscape composed of various nature sounds has the potential to present multiple channels of data simultaneously. Rich sound elements can also shape an immersive acoustic environment for relaxation.

Based on the nature soundscape (NS) model proposed in the previous chapter, we develop a new auditory interface—BioSoundscape, for a multi-channel biofeedback system. The main contributions of this chapter include:

- We applied the NS model to the design of BioSoundscape, in which the synthesized nature soundscape responds to the users' respiration, HRV, and arousal level.
- We evaluated the feasibility of BioSoundscape as a biofeedback interface and examined the possible effects of nature soundscape for stress management and relaxation training.

8.2 Design of BioSoundscape

Our prior work (in chapter 3) was mainly based on the parameter-mapping (PM) approach, where the input HRV data generate the audio outputs. When a valid IBI data is detected, according to the data value, the system then selects the audio content of different acoustic parameters. PM sonifications can explicitly and accurately display the data, like a bar chart in tachogram. The audio outputs can be very sensitive to the changes of data. This makes the PM approach perhaps suitable for monitoring data (Ciardi 2004), checking errors or medical diagnosis (Ballora et al. 2004). In auditory biofeedback for relaxation training, PM has some obvious drawbacks. For instance, before the physiological data is regulated to a targeted pattern, its temporary chaos is still sonified 'directly' so that the audio outputs sound less pleasant and even nerve-inducing.

Model-based sonifications (MBS) address this problem by introducing a 'mediator' between data and sound. Before interfacing with the dataset, a sound-generating model is developed first. The model generates the audio outputs. The input data can be regarded as a 'driver' for the model, manipulating its parameters.We think MBS approach has two advantages for biofeedback display in the context of stress management. Firstly, it can be 'always-on'. Even there is no bio-data input; the interface will still follow a set of pre-defined rules to produce sounds that can well blend into an everyday acoustic environment. Secondly, it offers more parameters to couple with the data. In addition to acoustic parameters, the expressive parameters of a model (e.g., the richness of the NS model) allow a 'natural coupling' with the data. The design of BioSoundscape has two steps, focusing on each of the above advantages.

8.2.1 Constructing a comforting NS

We firstly set up the sound library of a nature soundscape by selecting proper audio contents from real sound recordings. BioSoundscape is designed as an ambient interface that can blend into an indoor acoustic environment as a natural augment. It aims to offer a comforting nature soundscape that can keep playing whether with or without the physiological data being fed in. Based on the proposed NS model, we created the sound library of a forest soundscape which consists of wind sound as the climatic sound (Cs), a water stream for geophysical sound (Gs), and several types of birds (silvereye, wren, greenfinch, collared dove and cuckoo) for biological sounds (Bs), as shown in Fig 8.1.

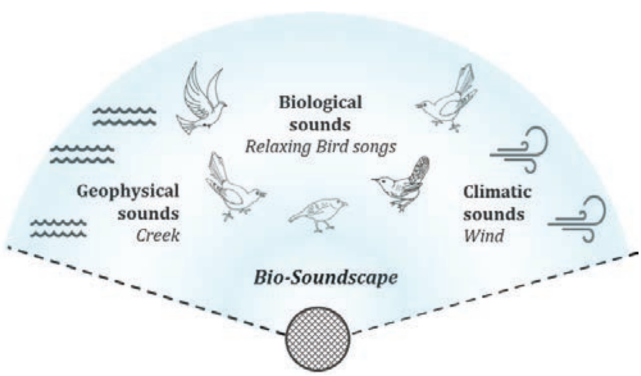

Fig 8.1
The composition of a forest soundscape as the sound library for BioSoundscape

8.2.2 Designing a 'natural coupling' for biofeedback display

After constructing the nature soundscape, the physiological data can be mapped to its parameters for biofeedback display. The NS model allows manipulating the attributes of a nature soundscape at 'perceptual' or 'experiential' levels by adjusting multiple acoustic parameters of different sounds jointly. The model suggests two attributes of NS can be manipulated effectively for information display — quietness, and richness. The quietness of NS has a negative correlation with the volume of Cs, Gs, and Bs. The richness of NS is mainly influenced by the type variations and the density of Bs. As such, the acoustic parameters of individual nature sounds are 'encapsulated' inside, while the perceptual attributes can be interfaced with the input data. As suggested by Rasmussen et al. (2012) and described in chapter 5, a shape-changing interface may offer two types of parameters to couple with the data: kinetic and expressive parameters. The expressive parameters account for "*how the effect of the kinetic parameters is perceived*". Similarly, we describe the perceptual attributes of the nature soundscape as its expressive parameters.

BioSoundscape consists of wind, water, and various bird sounds. Each of the wind and water sounds has one acoustic parameter—volume. The bird sounds have three acoustic parameters—volume, density and type variations. Beyond these acoustic parameters, the quietness and richness of the NS are used as two expressive parameters. In presentation mapping, the physiological data can be mapped to the acoustic parameter individually to present a physiological activity, such as heartbeat or breathing. The data can also be mapped to the expressive parameters, quietness, and richness, of the overall soundscape. In this design, BioSoundscape conveys one physiological process—respiration (RSP) and two physiological states: heart rate variability (HRV) data and arousal level. The presentation mapping from the data space to the sound space is shown in Fig 8.2.

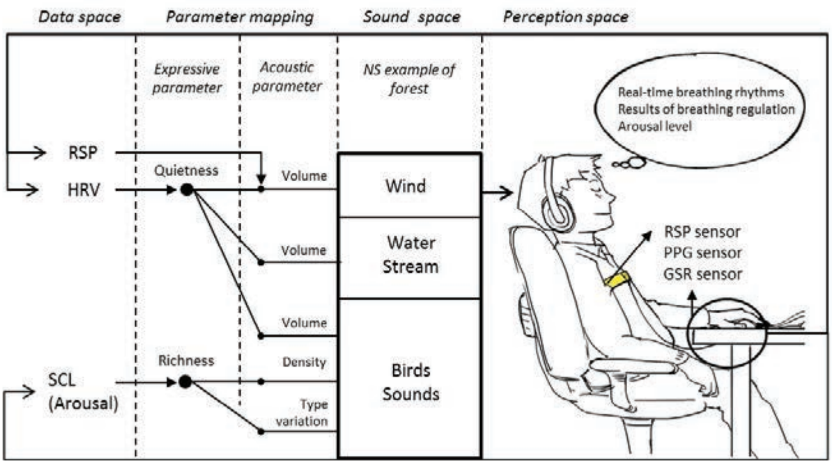

Fig 8.2 The presentation mapping from the biofeedback data to the parameters of BioSoundscape

Following the idea of 'natural coupling', BioSoundscape presents respiration (RSP) data through the changes in the wind volume. When the user breathes in, the wind becomes quiet. Conversely, when the user breathes out, the wind becomes loud. We assume this natural coupling between the user's breathing and the wind changes would be intuitive to understand. Secondly, BioSoundscape presents HRV data through the 'quietness' of the soundscape. In a relaxation training, HRV data indicate the results of breathing regulation. When a user performs well in deep breathing, the increased HRV will lead to a quiet soundscape by reducing the volume of all sounds. Otherwise, the soundscape will become loud to motivate the user to regulate breathing pattern. Thirdly, BioSoundscape presents physiological arousal level through the 'richness' of the soundscape. The richness of NS is controlled by modulating the density and type variations of the bird sounds. The arousal level is closely associated with a feeling of calm (low arousal) and stress (high arousal). When the user is in a calm state with a low arousal level, the richness will be reduced so that the soundscape becomes simple and pure. Conversely, in a high-arousal state, the user will hear the soundscape becoming dense and complex.

Table 8.1 The presentation mapping from the biofeedback data to the expressive parameters and corresponding acoustic parameters of different nature sounds

Biofeedback data	Expressive parameters	Involved Sound elements	Acoustic parameters
Breathing	Wind movement	Wind	Volume increment
Arousal level	Quietness	Wind, Water and birds	Volume
HRV level	Richness	Bird sounds	Density and type variations

8.3 Implementation of BioSoundscape

Fig 8.3 shows the framework of BioSoundscape system. The respiration (RSP), blood volume pulse (BVP), and skin conductance signals are measured by using a *NeXus-10* device (*MindMedia,* the Netherlands) with a sampling rate of 256 Hz. We implemented BioSoundscape program on *Processing* platform with *Beads* Java audio library. The program can be divided into three main parts: biofeedback processing, presentation mapping, soundscape synthesis (indicated by different colors in the dotted box, Fig 8.3).

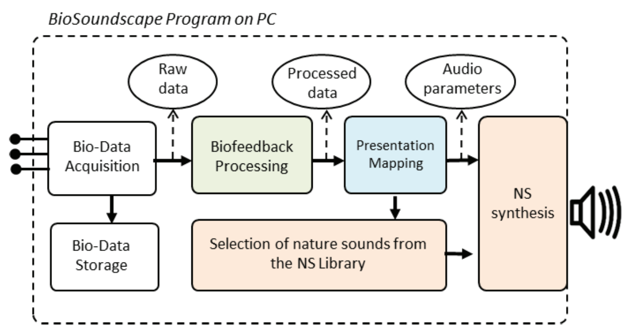

Fig 8.3
The system framework of BioSoundscape

The raw bio-signals are received and stored in the program for experimental analysis. In the meantime, the bio-signals are also processed for biofeedback. Fig 8.4 shows the program flow chart of BioSoundscape. In the biofeedback processing block (green), the RSP data is firstly downsampled from 256 Hz to 5 Hz (5 samples per second). We calculate the HRV_{16} as the short-term HRV index, see more details in chapter 5, section 5.3.2. The skin conductance level can slowly vary over time in an individual depending on his or her psychological state, hydration, and autonomic regulation. We calculated the average value of the skin conductance data in the window of 30 seconds as the measure of physiological arousal.

The audio display block (orange) produces the nature soundscape. The wind sound is generated with the wind-noise function provided by *Beads* Java audio library. The direction of the wind sound is adjusted with the *wind-noise.pan* function to switch between the left and right channels with a random cycle ranging from 5 to

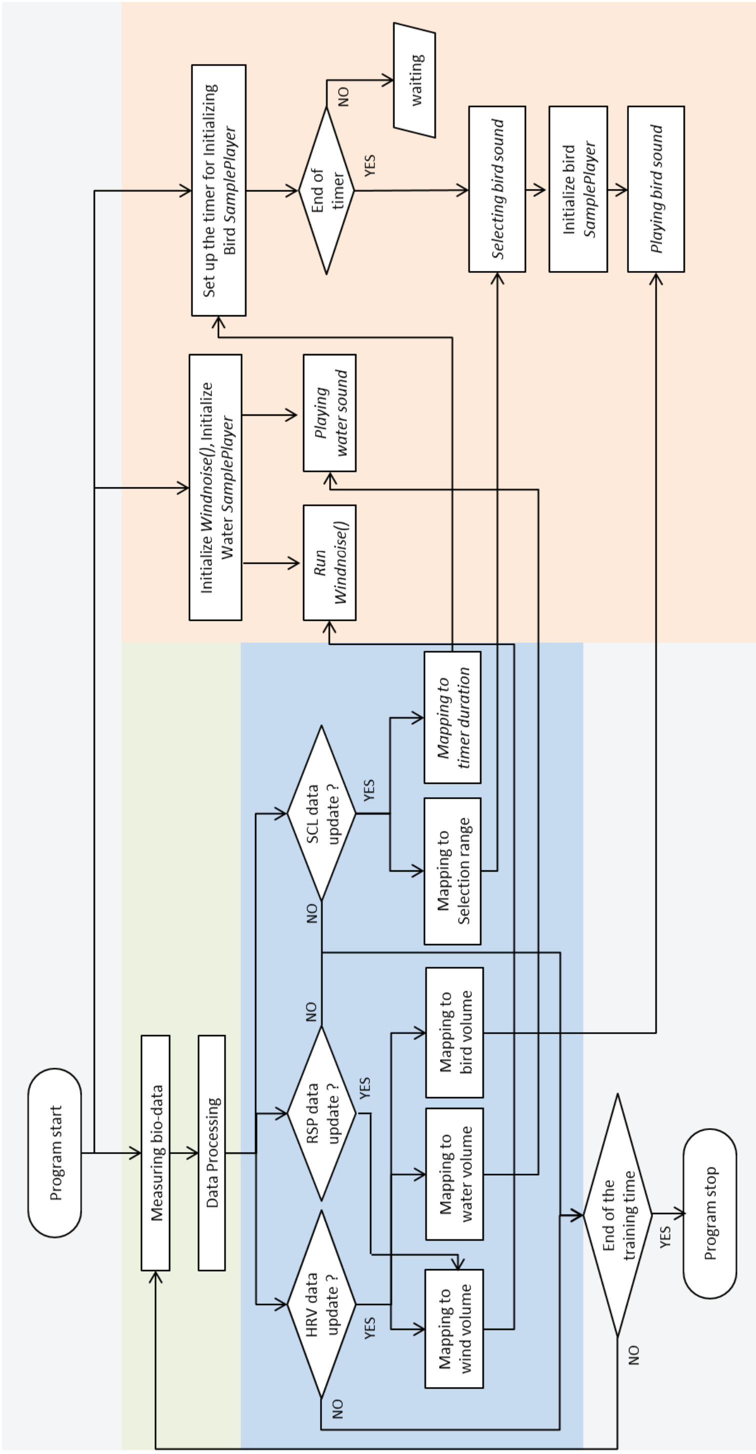

Fig 8.4 The program flow chart of BioSoundscape software

10 seconds. The intention here is to improve the realism of the wind sound. The audio files of water and bird sound are stored in the local folder and played by a corresponding *sample-player*. The *wind-noise* and the *sample-player* of water sound are instantiated when the program initializes. The instantiation of the bird sound *sample-player* is controlled by a timer whose period is adjusted by the data. The bird sound audio file is selected from the NS library in each instantiation.

In the presentation mapping block (blue), the calculated biofeedback data are mapped to the NS parameters with different updating frequencies. The HRV_{16} (0-225ms) is updated with each heartbeat and mapped to the basic amplification factor (0-0.1) of wind, water, and bird sound volume, influencing the quietness of the soundscape. The RSP data is updated at 5Hz and mapped to the increment and decrement on the basic wind volume (±20%). The SCL value is updated every 30 seconds, and mapped to the density and type variation of the bird sounds (Bs), influencing the richness of the soundscape. The density is controlled by setting a different duration of the timer to instantiate the *sample-player* of bird sounds. Here we map the baseline SCL to the default duration of the timer, that is 5000 ms. We map the SCL_{new} /SCL_{base} ratio (20%-180%) to the duration of the timer from 8000 ms to 2000 ms. When the SCL_{new}/SCL_{base} ratio decreases, the time's duration increases. In this way, a reduced arousal level will lead to a lower density of bird sounds. The nature soundscape contains five types of bird. Each type of bird sound contains five samples with certain variations. As such, there are in total 25 bird sound samples in the soundscape library. Each time the *sample-player* of bird sounds is instantiated, the SCL_{new}/SCL_{base} ratio determines the range of the sample selection (5 to 25 samples). A reduced arousal level will lead to a smaller range of selection. The range of breathing depth and the baseline of skin conductance level (SCL_{base}) vary from person to person. As such, before the biofeedback session, we measure the maximum and minimum of respiration data and the baseline of SCL for each participant.

8.4 User Experiment

BioSoundscape is designed with two primary functions: the informative function as a biofeedback display and a comforting acoustic environment for relaxation. There are two hypotheses we studied in the user experiment:

- **Hypothesis 1:** The nature soundscape developed with the NS model can enhance relaxation effects physically and mentally.
- **Hypothesis 2:** The biofeedback through BioSoundscape can facilitate the self-regulation (breathing regulation) in the relaxation training.

8.4.1 Participants

Thirty participants (16 females, 14 males, age range: 24–33 years) were recruited by an online advertisement. Participants were compensated with 5 Euros for their participation. The participants did not practice yoga, meditation or deep breathing exercise regularly. Furthermore, the participants did not have any experience with biofeedback. All participants gave informed consent before participating.

8.4.2 Experimental design

We evaluated BioSoundscape in a between-group experiment. After a mentally challenging (potentially stressing) task, the participants were randomly assigned to one of three conditions for relaxation: silence (CTRL), pre-set nature soundscape (NS) and BioSoundscape biofeedback (NSBFB). In the CTRL condition, the participants relaxed in silence. In the NS condition, the participants were exposed to a piece of nature soundscape controlled by the program. In the NSBFB condition, the participants listened to BioSoundscape that was controlled by their bio-data in real time. In all conditions, the participants were suggested to perform deep breathing for relaxation. In NSBFB condition, they were told that the wind sound would increase and decrease with their breathing and when they perform well in deep breathing, the soundscape will become quiet. When they are more relaxed (low arousal), the soundscape will become simple and pure.

8.4.3 Measurements

The participants reported their stress/anxiety level through the Relaxation Rating Scale (RRS) and State-Trait-Anxiety-Inventory (STAI-S) questionnaires. The RRS is a simple self-reported instrument that is used to assess the degree of subjective relaxation experience. The RRS requires the participant to rate his/her relaxation level on a Likert-type scale with one being 'not relaxed at all' and nine being 'totally relaxed.' The State Anxiety subscale of the State-Trait Anxiety Inventory (STAI-S) is a 20-item self-report survey, which requires an individual to rate how he or she feels 'at this moment.' Higher scores indicate a higher level of anxiety and stress.

Physiological measurements included respiration rate (RSP-R), heart rate (HR), heart rate variability (HRV-LF%), and Skin Conductance Responses (SCRs). The bio-signals were measured by using the *Nexus-10* amplifier and stored individually in the BioSoundscape program. A respiration strap sensor was placed on the abdomen across the participant. The strap was adjusted so that there was a slight tension when the participant fully breathed out. The IBI data was measured by a PPG sensor on the index finger and analyzed in *Kubios* software to obtain the average HR and power percent in low frequency of HRV (HRV-LF%). Each electrode of the skin conductance sensor was strapped to 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 skin conductance (SC) data was analyzed in *Ledalab* 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 level (refer to [Boucsein 2012] for more details about electrodermal activity).

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1. *Kubios* software, *https://www.kubios.com/, retrieved:13-11-2017.*

2. *Ledalab software, http://www.ledalab.de/, retrieved:13-11-2017.*

8.4.4 Procedure

The experiment followed the procedure in Fig 8.5. All participants were tested individually in a small testing room furnished with a recliner chair, rug, lamps, and the biofeedback system. The participants completed a demographics questionnaire first. After being attached to the bio-sensors, the participants sat quietly for 5 minutes during which the baseline of the physiological measurements was recorded. Then, they completed the STAI-S and RRS. Next, the participant was administered a 10-minute mirror-tracing task for stress induction. After the task, the participant completed the STAI-S and RRS again. Next, the participants were told that they would either relax in silence, listen to a piece of nature soundscape, or receive biofeedback through BioSoundscape for 10 minutes. After this part, they completed the STAI-S and RRS surveys again. In all conditions, the participants wore acoustic noise-canceling headphones (*Bose, QuietComfort 25*) to block environment noise. The sounds were played through the headphone. Finally, all physiological sensors were detached, and the participants left the lab.

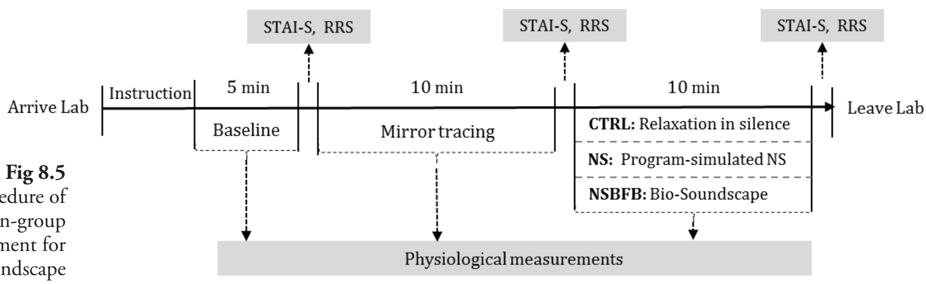

Fig 8.5
The procedure of the between-group experiment for BioSoundscape

8.5 Results

During the experiments, the inter-beat interval (IBI) data was not detected for three participants due to the problem of cold hands and fingers. For the rest of the valid measurements, a one-way ANOVA was conducted to test the effectiveness of BioSoundscape on self-regulation assistance and relaxation promotion. A post hoc test using the Tukey HSD was conducted to report the differences occurred between the conditions. Table 8.2 provides an overview of the descriptive statistics.

8.5.1 Physiological data

Heart Rate. Fig 8.6(a) shows the percent changes in the average heart rate (relative to their levels under the mentally challenging task) between three conditions. The participants in the NS (M=–6.7%, SD=6.5%) and NSBFB (M=–7.2%, SD=7.4%) conditions showed a large reduction in heart rate. The HR in control condition (relax in silence) showed a small decrease. There was no significant difference in heart rate between the three conditions [$F(2, 24)=1.14$, $p=0.34$].

Skin Conductance Responses (SCRs). Fig 8.6(b) shows the percent changes in the number of SCRs (relative to their levels in the mentally challenging task) in each

Condition	CTRL	NS	NSBFB		CTRL	NS	NSBFB
HR	%			***SCRs***	%		
N	9	9	9	N	10	10	10
Mean	−2.76	−6.68	−7.18	Mean	4.28	−44.25	−57.22
Std.D	6.37	6.53	7.48	Std.D	56.94	20.34	21.86
Std.E	2.12	2.18	2.49	Std.E	18.00	6.43	6.91
RSP-R	%			***HRV***	%		
N	10	10	10	N	9	9	9
Mean	−20.73	−10.89	−43.38	Mean	−15.69	−12.61	23.02
Std.D	10.00	11.51	12.69	Std.D	14.71	29.87	45.47
Std.E	3.16	3.64	4.02	Std.E	4.90	9.96	15.16
RRS	score			***STAI***	score		
N	10	10	10	N	10	10	10
Mean	2.2	3.3	3.0	Mean	−3.6	−5.6	−11.2
Std.D	1.135	2.451	2.054	Std.D	4.033	7.486	9.589
Std.E	0.359	0.775	0.649	Std.E	1.275	2.367	3.032

Table 8.2 Descriptive statistics of physiological data and the subjective self-reports for each of the three conditions (columns). The percent changes in physiological data are calculated relative to their levels during the mentally challenging task for each of the three conditions. For each data stream, the number of valid data points (N), the Mean, standard deviation (Std.D), and standard error of the mean (Std.E).

of the three conditions. There was a significant effect of listening to the nature soundscape on the SCRs [$F(2, 27)=7.627$, $p<0.05$]. A Tukey post hoc test revealed that the decrease of SCRs in the NS (M=−44.3%, SD=20.3%, $p<0.05$) and the NSBFB (M=−57.2%, SD=21.8%, $p<0.01$) conditions were significantly larger than in the control condition (M=4.3%, SD=56.9%). However, the SCRs data under the NSBFB condition did not significantly differ from the NS condition ($p=0.72$).

Respiration-Rate (RSP-R). Fig 8.6(c) shows the percent decrease in average respiration rate (relative to their levels in the mentally challenging task) in each of the three conditions. There was a significant effect of biofeedback on the respiration rate [$F(2, 27)=21.17$, $p<0.01$]. A Tukey post hoc test revealed that the RSP-R under the NSBFB condition (M=−43.38%, SD=12.7%, $p<0.01$) was significantly lower than the NS condition (M=20.7%, SD= 9.9%) and control condition (M=10.9%, SD=11.5%, $p<0.01$). There was no significant difference between the NS and control conditions ($p=0.15$). These results suggest that the respiratory biofeedback through BioSoundscape greatly encouraged the breathing regulation of the participants, leading to a slow and deep respiration pattern.

Heart Rate Variability. We used LF/(LF+HF), also named as LF%, as the HRV index. Fig 8.6(d) shows the percent changes in HRV (relative to their levels in the mentally challenging task) for three conditions. There was a significant effect of biofeedback on HRV [$F(2, 24)=3.93$, $p<0.05$]. A Tukey post hoc test revealed that the increase of HRV in NSBFB condition (M=23.0%, SD=45.5%, $p<0.05$) was significantly higher than control condition (M=−15.7%, SD=14.7%). As suggested by Schipke et al. (1998), the interpretation of the HRV indices depends on the recording context. In short-term recordings, HRV can be highly related to the respiratory cycle. Especially when an individual takes a few deep breaths around 10 seconds cycles, the power spectrum of LF band will burst around 0.1Hz. Therefore, in this study, HRV-LF% serves as a criterion of biofeedback effects on breathing regulation, not the indicator of physiological stress. The results of HRV are consistent with the results of respiration rate, suggesting that the BioSoundscape could facilitate deep breathing effectively due to the respiratory biofeedback.

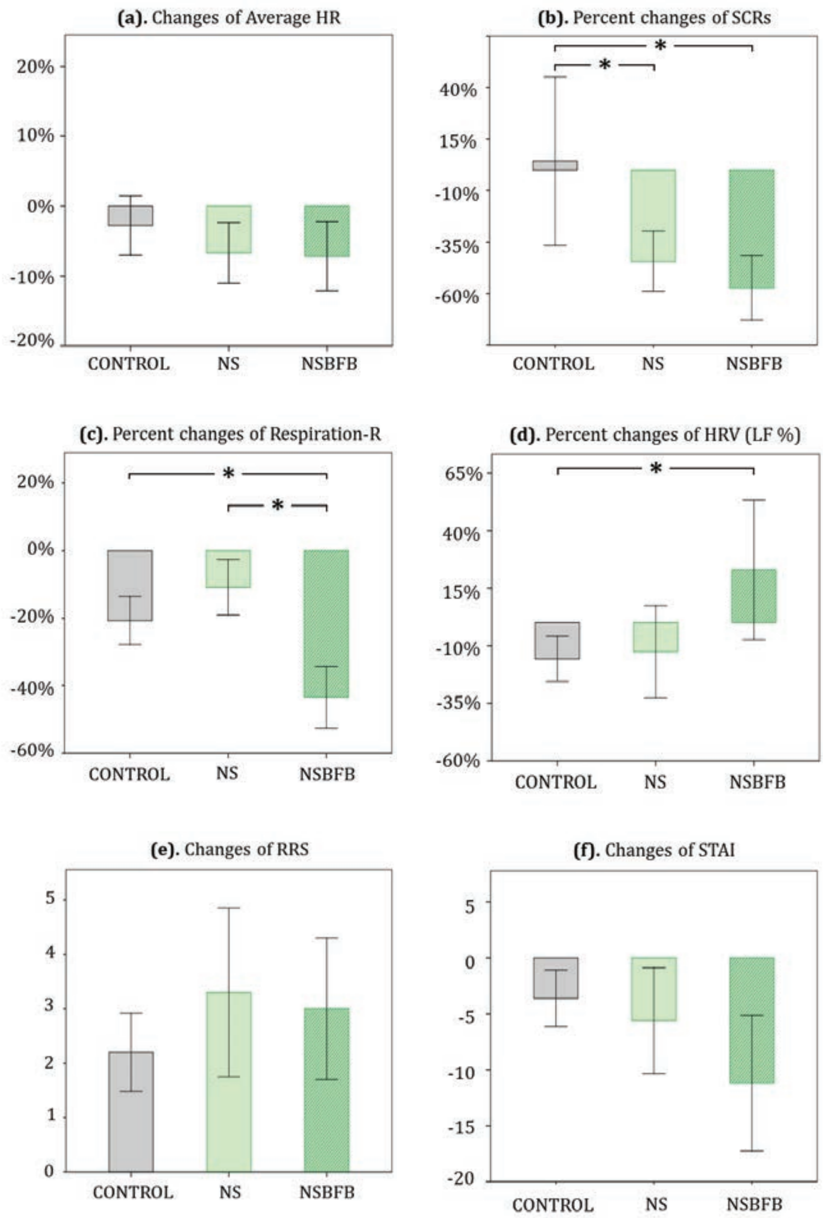

Fig 8.6 the results of the physiological data and self-report surveys

8.5.2 Self-report Surveys

Fig 8.6 (e) and (f) show the changes in RRS and STAI-S scores (relative to their levels in the mentally challenging task) for three conditions. The RRS was increased after the relaxation in all conditions: the control (M=+2.2, SD=1.14), NS (M=+3.3, SD=2.45) and NSBFB (M=+3.0, SD=2.05) condition. The participants reported a higher relaxation level in NS and NSBFB conditions than control condition, but the difference was not significant [$F(2, 27)=0.84$, $p=0.44$]. As shown in Fig 8.6(f), the participants reported a decrease in STAI-S score in the three conditions as well. Although there was no significant difference between three conditions on STAI-S scores [$F(2, 27)=2.83$, $p=0.076$], the decrease in the STAI-S score in NSBFB condition was larger than in control and NS conditions, which suggests that the BioSoundscape has the potential in reducing the subjective anxiety feelings in a relaxation exercise.

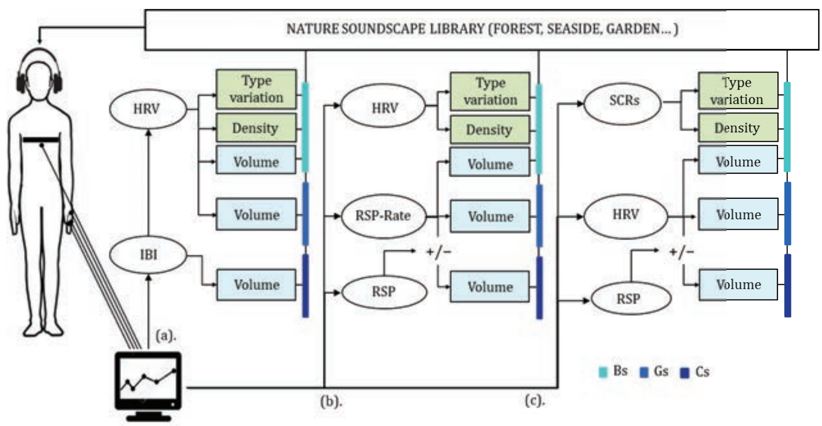

Fig 8.7 Examples of auditory biofeedback interface developed based on the NS model

8.6 Discussion

This work started out at the intersection of biofeedback, nature soundscape, and model-based sonification. Nature sounds are used as an information carrier and also an auditory stimulus to enhance the user's relaxation effects during biofeedback training. BioSoundscape is developed based on the proposed nature soundscape (NS) model. The NS model provides a coherent context and a simplified framework to select and construct the nature sounds library. And then, in the presentation mapping, the nature sounds are tuned and modified by different bio-data in the way that the resulting soundscape becomes informative for biofeedback but also perceived and experienced as a harmonious acoustic environment. Regarding the information display, BioSoundscape explicitly presents the user's breathing rhythm with the wind sound and indicates HRV and arousal level through the quietness and richness of the overall soundscape. As such, in a relaxation training, the user can focus on the breathing regulation by controlling the wind, and learn their HRV and arousal level through the quietness and richness of the soundscape. Regarding user experience, BioSoundscape offers a more comfortable and relaxing condition to use biofeedback technique with eyes closed and fewer constraints on the place of use. The results of the experiment confirmed our hypotheses. The nature soundscape developed with the NS model could help the users relax physically (lower HR and SCRs) and mentally (higher RRS and lower STAI score). Moreover, the biofeedback through BioSoundscape could facilitate the users to regulate the respiration into a deep and slow pattern (lower RSP-R).

BioSoundscape presented in this chapter (with a 'forest' theme) is one of the many possible instantiations of the NS model. Other NS libraries of different nature themes can be built for different applications and contexts. BioSoundscape can also interface with different biofeedback systems. In this chapter, we explored using BioSoundscape as an auditory interface for a multi-model biofeedback system, as shown in Fig 8.7(c). It can also be interfaced with a dual-channel HRV and respiration biofeedback system, see Fig 8.7(b). In the case of a single channel HRV biofeedback (Fig 8.7-a), BioSoundscape can provide rich auditory expressions by linking the limited heartbeat data to multiple nature sounds jointly. Take the example of the HRV biofeedback system described in chapter 3-5, the wind sound can present IBI data, and HRV_{16} data can be presented by the quietness and richness of the NS. This idea has been explored in the design of RESonance, see chapter 10.

In this chapter, we have established that the NS-model based auditory biofeedback could facilitate the breathing regulation and efficiently reduces the arousal level. The nature soundscape shows positive effects on stress relief and relaxation. We view these results as an encouraging indication that nature sounds can be a proper information 'carrier' for biofeedback display and also a 'booster' for relaxation. We think BioSoundscape can be combined with music as a musical biofeedback interface, in which nature sounds can act as the 'information layer' interfacing with the data source and the music can further boost mood and evoke positive emotions. This concept will be explored in the design of UnWind, see Appendix D.

9

DeLight: Biofeedback through Ambient Light

9.1 Introduction

Besides nature sounds, light is a common means of ambient displays because it is rich in parameters for presenting information but also can evoke moods and create immersive experiences. In this chapter, we explored a lighting interface for biofeedback. Our exploration started at the intersection of lighting design, biofeedback technique, and relaxation training. Through the design of DeLight, we investigated how ambient light could be used as a medium to both present physiological information but also promote relaxation. This chapter mainly focuses on the following goals: 1). design a new biofeedback interface with ambient light, and 2) evaluate its effectiveness on relaxation training.

9.1.1 Lighting interface in HCI

Light as an integral part of everyday settings, is a good ambient media to portray additional information. Its basic parameters, including brightness, hue, and saturation, can be directly coupled with input data. More advanced lighting systems can encode information using dynamic patterns of multiple lights, such as brightness distribution. As an alternative to on-screen visual displays, lighting interfaces can be aesthetically pleasing, decorative, and unobtrusive. For instance, *AmbiX* presents an overview of information updates through the light in household and office settings (Müller et al. 2012). Occhialini et al. (2011) used lighting displays to support time management during meetings. Maan et al. (2011) used ambient light to indicate the energy consumption, which showed a stronger persuasive effect than numerical feedback. Fortmann et al. (2013) used the office light to indicate inhabitants' recent physical activity for motivating them to move more frequently. *MoodLight* is an interactive ambient lighting system that

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This chapter is largely based on

Yu, B., Hu, J., Funk, M. and Feijs, L. (Under Review) Delight: Lighting Biofeedback for Stress Management *Personal and Ubiquitous Computing* presents feedback on an individual's current level of arousal (Snyder et al. 2015).

Light, as an environmental stimulant, has a particular ability to create atmosphere, evoke moods, and provide immersive experiences. For instance, *Flower Power* (Monaci et al. 2011) projects a set of saturated changing lights on the wall of public space to create immersive experiences for the audience. *In IllumiRoom* (Jones et al. 2015), the ambient lights adapt to the theme of a PC game. The lights blur the boundary between the on-screen displays and the surroundings for enhancing the players' experience. Similar examples can also be found in commercial products, e.g., the Philips *AmbiLight*[1] system. Besides, lights can be a great focus for meditation or guided relaxation. For instance, Ståhl et al. (2016) designed an ambient light that dims in cadence with the user's breathing to support a meditative bodily experience.

9.1.2 Light and relaxation

Several lines of evidence suggest that colored light can provoke emotional and physiological responses. Colored light has an impact on the autonomic nervous system (ANS), influencing various physiological activities including breathing, heart rate, and the stress response(Liberman 1990; Breiling 1995). Ross et al. (2013) examined the effects of different light color on individuals' physiological arousal and subjective feelings of energy or calmness. Specifically, a warm-colored light (red, orange, yellow) may improve the arousal level and the feeling of alertness and energy, while a cool-colored light (green, blue, indigo) may reduce the arousal and lead to a feeling of calmness. A lighting environment with carefully-set color and intensity may have specific mood-enhancing or relaxation effects. For instance, a dimmed ambient lighting environment is often used for relaxation training (Lysaght & Bodenhamer 1990). Colored light therapy (Cocilovo 1999; Golden et al. 2005) has been increasingly practiced by many clinicians to assist stress management and relaxation practice and to treat psychosomatic disorders. Similar examples can also be found in various commercial products. For instance, *Philips luminous textile*[2] uses the colored light creating 'De-stress' waiting areas in the hospital to help patients feel energized or relaxed. The *f.lux* software[3] and the comparable '*Night Shift*' setting on iOS adjust the color of the display based on the time to influence the melatonin level and help to wind down in the evenings and possibly address mild sleeping disorders.

9.2 Design and Implementation of DeLight

The goal of DeLight is not only for ambient biofeedback display, but also to provide an immersive relaxing experience. We believe the combination of decorative and informative aspects can make ambient light both pleasant and helpful for users.

1. Philips AmbiLight system, https://www.philips.co.uk/c-m-so/televisions/p/ambilight, retrieved:13-11-2017

2. Philips luminous textile: http://www.lighting.philips.com/main/products/luminous-textile, retrieved:13-11-2017

3. F.lux software: https://justgetflux.com/, retrieved:13-11-2017

9.2.1 DeLight biofeedback system

DeLight is an HRV biofeedback system which presents the IBI and HRV data. As shown in Fig 9.1, DeLight system consists of three parts: a bio-sensing device, a biofeedback program, and a lighting system. The biofeedback data processing is same as the previous chapters, see chapter 5, section 5.3.2. The IBI and HRV data are calculated from BVP signal and coupled with the parameters for lighting control. A set of programmable light bulbs (*Philips Hue*[4]) was employed to set up the lighting system. DeLight consists of a center light and several ambient lights. The center light is a portable HUE lamp which is held in the hands, close to the body of the users. The ambient lights are installed on the ceiling or projected on the wall, creating the ambiance of the indoor environment. The Hue SDK allows adjusting the color and intensity of lights by real-time data via a Wi-Fi connection.

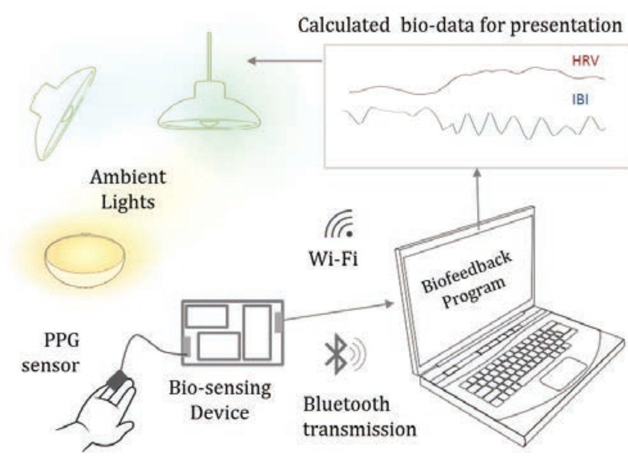


Fig 9.1
The system framework of DeLight biofeedback system

9.2.2 Presentation mapping for lighting display

DeLight aims to facilitate resonant breathing during relaxation training. DeLight presents the IBI data by modifying the distribution of brightness between the center and ambient lights and indicates the results of breathing regulation (improved HRV) by adjusting the color of the lights. The instantaneous IBI data is directly fed back to the users for assisting breathing regulation. The HRV data indicates the results of breathing regulation. Here we calculate HRV_{16} as the HRV index. Table 9.1 shows the mapping between the IBI and HRV data to the lighting expressions and the traditional graphic display.

We applied the 'natural coupling' in the presentation mapping. As shown in Fig 9.2, the lighting display of IBI data is designed around the idea of 'exchange'. Breathing is a process of gas exchange, where we breathe in oxygen and breathe out carbon dioxide. With the DeLight system, as an individual user inhales, the air flows into the body and the heart rate increases, causing the brightness transferred

4. *Philips Hue: http://www2.meethue.com/nl-nl/, retrieved:13-11-2017*

Table 9.1 The presentation mapping from IBI and HRV data to lighting parameters

Biofeedback data	*DeLight lighting display*	*On-screen graphic display*
HRV_{16}	Color of center and ambient lights	Background color of the displayed waveform and the application window
IBI	Brightness interchange between center and ambient lights	Fluctuation of the waveform

from the ambient lights to the center lights close to the body. Conversely, on exhalation, the air flows out from the lungs, and accordingly, the brightness is transferred back to the ambient lights at a distance. We assume that the brightness transfer back and forth between the center and ambient lights can be naturally associated with the user's breathing movement and intuitive to understand. Specifically, the IBI data (450 to 1250ms) are mapped to the brightness value from 0 to 255 for the ambient lights and from 255 to 0 for the center light.

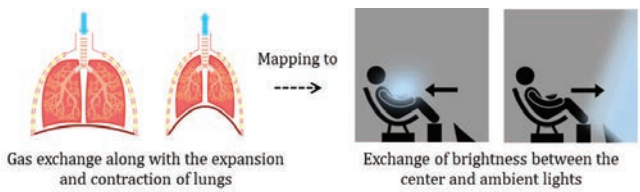


Fig 9.2 The natural coupling between IBI data and brightness distribition

The short-term HRV indicates the results of breathing regulation, which helps the users to enhance their confidence during relaxation training. We used the color of lights to indicate the HRV level. Specifically, the parameter of hue was set to a fixed value of 45000 (cyan-blue), and the saturation value ranging from 0 to 250 was coupled to HRV_{16}. In this way, a color of a low saturation (close to white light) indicated a low level of HRV. Conversely, the highly-saturated blue light indicated an improved HRV.

As shown in Fig 9.3, at the beginning of the relaxation training, the IBI data showed subtle variations. The distribution of brightness did not change significantly, and the color of lights remained cool white. With the user's breathing became slow and deep, the IBI change in an approximate sinusoidal pattern, and accordingly, the brightness was 'transferred' between the center and ambient lights periodically. The improvement of HRV drove the light color changing from white to blue.

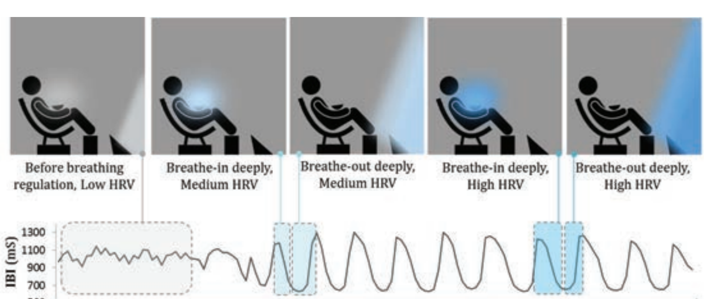


Fig 9.3 The presentation mapping between lighting displays and the IBI and HRVdata

9.3 Evaluation

A user study was conducted to answer two main questions: 1. whether the biofeedback display through DeLight can be perceived as effectively as the traditional graphic biofeedback for relaxation training and 2. whether the biofeedback lighting environment would offer users a more desired and relaxing experience? Hence, we designed a within-subject experiment, in which all participants would complete two biofeedback-assisted relaxation sessions: one with DeLight and the other with the on-screen graphic display. We hypothesized that DeLight would be equally effective as the graphic interface regarding information display, but would offer a more comfortable and enjoyable experience for relaxation. Fig 9.4(a) shows the set-up of DeLight biofeedback system for relaxation training. As shown in Fig 9.4(b), the GUI program presents IBI data by a waveform in the window of white background. The waveform color and background color of the frame area indicate the HRV level.

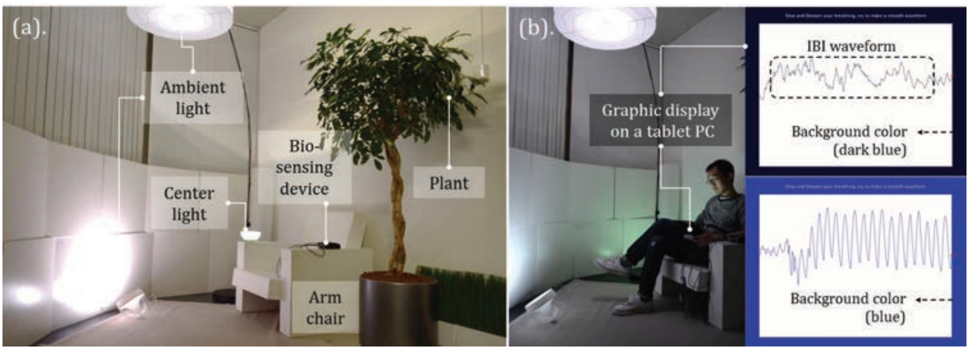


Fig 9.4 (a) The setting-up of DeLight for the experiment (b) the graphic display on the tablet

9.3.1 Participants

20 students (11 females and 9 males, age range: 25 to 35) participated in this experiment.Those who have the history of diagnosed cardiac or psychiatric disorders or technically unable to use the biofeedback system were excluded. All participants have never received any medical HRV or RSA biofeedback training.

9.3.2 Experiment procedure

The experiment followed the procedure shown in Fig 9.5. On arrival at the laboratory, the participants were fitted with a PPG sensor, a pair of SC sensors on the fingers and a respiration belt sensor on the abdomen. The participants sat quietly and relaxed for five minutes, during which their physiological data and subjective relaxation ratings were measured as the baseline. After this resting period, participants completed a 5-minute Stroop color-word test[5] for experiencing a simulated stressor. The physiological data and subjective relaxation ratings were also collected. Next, the participant undertook two relaxation training

5. Stroop color-word test: http://s3.mirror.co.uk/click-the-colour-and-not-the-word/index.html, retrieved:13-11-2017 sessions separately with biofeedback through graphic or lighting displays. Each relaxation session lasted 5 minutes. The order of the sessions was randomized to counterbalance carry-over effects. To prevent order effects, participants were asked to complete the Stroop color-word task again between two biofeedback sessions. This ensured the disruption of any regularized breathing patterns that participants might have practiced.

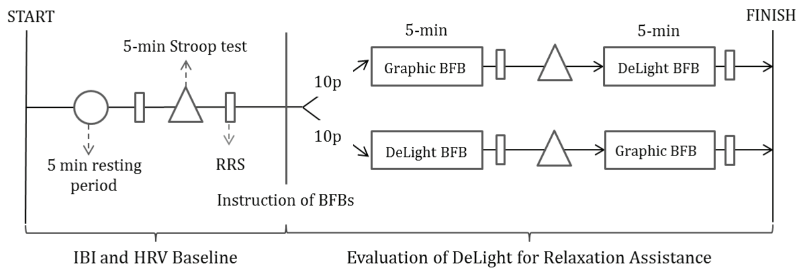


Fig 9.5
The procedure of the within-subject experiment for DeLight

9.3.3 Biofeedback protocol

Before each relaxation session, a corresponding instruction was given to the participants for guiding them how to use feedback information to improve the heart rate variability. During the graphic biofeedback relaxation session, the feedback is presented by a graphic user interface on a tablet PC screen. The instructions were: "*The waveform on the screen represents heartbeats intervals. When you breathe-in, the waveform rises, and when you breathe-out, the waveform declines. Try to make the waveform in a smooth sinusoidal form by adjusting your breath. When you breathe more slowly and deeply, the waveform becomes more smooth and regular, and the color of the waveform and frame color will be getting closer to blue.*"

For the DeLight relaxation session, the following instruction was given to the participants: "*The brightness of the lighting is controlled by your heartbeats intervals. When you breathe-in, the center light (portable lamp hold in your hand) will be brighter, and the ambient lights (floor and ceiling lamps) will be darker. When you breathe-out, the ambient lights will be brighter, and the center light will be darker. Try to make the brightness transfer between the center and ambient lights periodically by regulating your breath. You breathe more slowly and deeply, the brightness transfer becomes more smooth and regular, and the color of the light will be getting closer to blue.*"

9.3.4 Measurements and data analysis

The independent variable was the biofeedback interface, while the dependent variables consist of subjective relaxation rating and physiological measurements. We collected the participants' subjective relaxation feeling with the relaxation rating scale (RRS). The participants completed the RRS after the pre-test resting period, Stroop test, and two relaxation sessions immediately. The physiological measurements are same as the previous chapter, including heart rate, HRV indices, skin conductance responses (SCRs) and respiration rate.

9.4 Results

As shown in Fig 9.6, by interacting with DeLight, the participant's heart rate variations were dynamically coupled with the brightness and the color of lights, creating an immersive lighting environment. Before the biofeedback session (a), the brightness was nearly unchanged and evenly-distributed between the center and ambient lights. The light color was close to white in this initial state. At the beginning of the session (b, c), the brightness started to be distributed to different locations at the moments of inhalation and exhalation. However, the lights were still colorless as the participant's HRV is at a moderate level. Along with the deep breathing in relaxation training, the IBI oscillation was enhanced. Fig 9.6 (d) and (e) show the lighting effects when the HRV is at a high level.

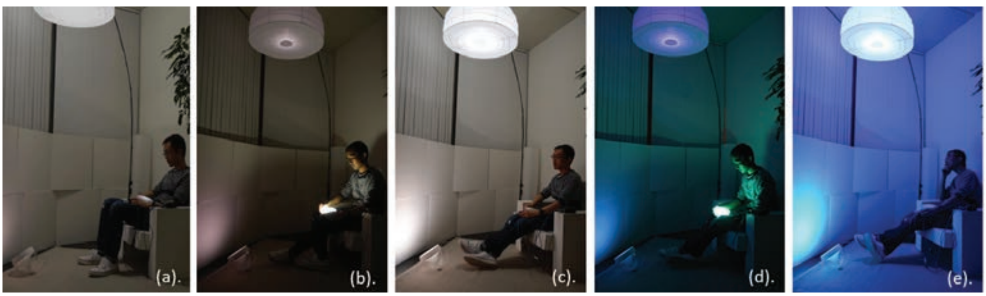


Fig 9.6 the changes of brightness distribution between the center light (b) and the ambient light(c) responding to the breathing regulation, and from white (c) to blue (e) color indicating an improved HRV

During the experiment, the IBI data were not detected for three participants due to the problem of cold hands and fingers. Further, the skin conductance data was missing from one participant because the sensors were disconnected with the skin. The respiration signals were not recognized for three participants, because the sensor belt loosened, which caused a loud motion artifact. The rest of the measurements were valid and examined through the Shapiro-Wilk test. For those measures that fit the normal distribution, a repeated measures ANOVA was conducted. Where the ANOVA was significant, a post-hoc analysis was conducted using paired samples t-tests to identify which conditions differed significantly. For those measures for which the Shapiro-Wilk test indicated a non-normal distribution, a nonparametric paired Wilcoxon test was conducted.

9.4.1 Physiological data

Heart Rate. A repeated measures ANOVA showed that the average HR differed significantly between the sessions, $F(2.224, 35.585)=8.626$, $p<0.01$, see Fig 9.7(a). Compared to the resting baseline ($M=72.98$, $SD=11.62$), the HR increased during the stress session ($M=74.81$, $SD=11.17$). Surprisingly, the HR also increased in the relaxation session with graphic biofeedback (*M*=75.95, *SD*=12.25) and the increase was even significant than the baseline, $t(16) = -1.85$, $p<0.05$. During the relaxation training with DeLight biofeedback, the HR was reduced (*M*=70.38, *SD*=9.52). Taken together, our results suggest that when participants performed relaxation training with the lighting biofeedback, they showed a slower heart rate. Interestingly, it should be noted that the traditional graphic biofeedback increased the participants' heart rate during the relaxation training.

Skin Conductance Responses (SCRs) A repeated measures ANOVA determined that SCRs differed significantly between baseline, stress, and two biofeedback relaxation sessions ($F(1.95, 35.18)=18.77$, $p<0.01$). Fig 9.7(b) shows the number of SCRs for each session. A paired t-test demonstrated the SCRs in the stress session (*M*=33.36, *SD*=16.37) was significantly higher than the baseline (*M*=15.68, *SD*=10.78, $t(18)=-7.5$, $p<0.01$). Compared to the stress session, the SCRs in graphic biofeedback session (*M*=22.6, *SD*=13.65) was decreased, but still significantly higher than the baseline, $t(18)=-3.52$, $p<0.01$. In DeLight biofeedback session, the SCRs stayed at a low level (*M*=16.37, *SD*=12.4), which had no significant difference to the baseline ($t(18)=-0.32$, $p=0.76$). From this data, we can see that ambient lighting biofeedback resulted in the lower arousal level during the relaxation training.

Respiration-Rate (RSP-R). A repeated measures ANOVA determined that respiration rate differed significantly between the baseline, stress session, and two biofeedback sessions ($F(1.63, 26.14)=56.16$, $p<0.01$). Fig 9.7(c) shows the average respiration rate (RSP-R) for each session. A paired t-test demonstrated the average RSP-R during the stress session (*M*=20.95, *SD*=5.42) was significantly higher than the baseline (*M*=15.86, *SD*=4.27, $t(16)=-4.44$, $p<0.01$). In contrast, compared to the baseline, the RSP-R decreased significantly during both graphic biofeedback (*M*=7.77, *SD*=2.88, $t(16)=5.8$, $p<0.01$) and DeLight biofeedback session (*M*= 6.78, *SD*=1.98, $t(16)=7.8$, $p<0.01$). There was no significant difference between two biofeedback sessions. The results suggest that the hypothesis that the lighting display of DeLight was as informative as the traditional GUI could not be rejected. The biofeedback information from both interfaces greatly promoted the breathing regulation during the relaxation training.

Heart Rate Variability. Fig 9.7 (d) and (e) show the results of RMSSD and LF%. A Friedman test demonstrated a significant difference in RMSSD ($X^2(3) = 9.07$, $p<0.05$), and in LF% ($X^2(3) = 21.96$, $p<0.01$), between the sessions. A Wilcoxon nonparametric test demonstrated the RMSSD improved significantly in graphic biofeedback ($Z=-2.15$, $p<0.05$) and DeLight biofeedback session ($Z=-2.343$, $p<0.05$) compared to the baseline. Similarly, LF% also improved significantly in graphic biofeedback ($Z=-3.15$, $p<0.01$) and DeLight biofeedback session ($Z=-3.34$, $p<0.01$). No statistically significant difference between graphic and DeLight was shown in RMSSD and LF%. The results of HRV were consistent with respiration results and further confirmed that DeLight could be an alternative to GUI-based biofeedback display. The users could perceive the IBI feedback effectively through ambient light and use it in breathing regulation, which leads to an improved HRV.

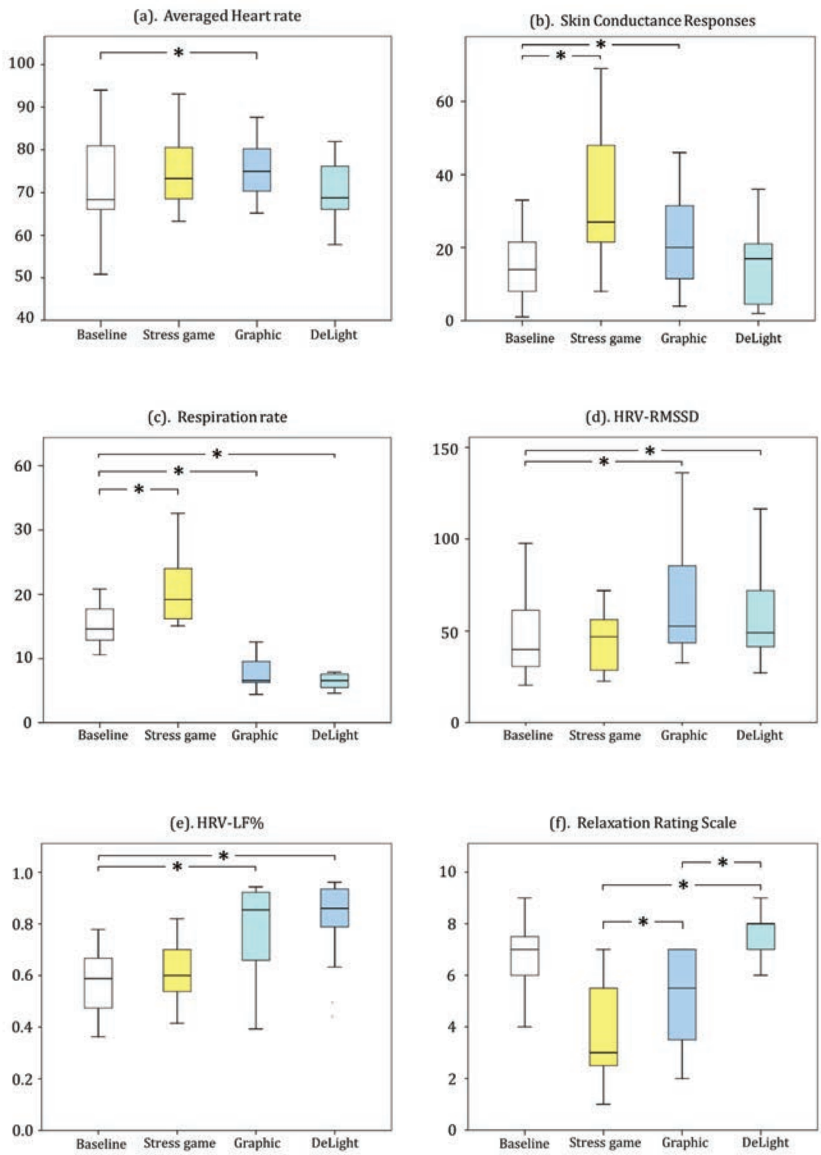


Fig 9.7 The results of the experiment (a). averaged heart rate (HR) (b). skin conductance responses(SCRs) (c). respiration rate (d). HRV-RMSSD (e). HRV-LF% (f).relaxation rating scale

Breathing Pattern. The observation of the breathing pattern is interesting for understanding how the participants used the feedback information to regulate their breathing. Fig 9.8 shows a typical set of breathing pattern during the relaxation sessions. We found that the process of breathing regulation during the biofeedback-assisted relaxation session could be broadly divided into three phases: the adjustment phase, the stabilized phase, and the fatigue phase. As shown in Fig 9.8(a), with graphic biofeedback, it took some time for the participant to get familiar with, understand and utilize the feedback in breathing regulation. With lighting biofeedback, this phase of adjustment seemed to be shortened, see Fig 9.8(b), and even not needed for some participants, see Fig 9.8(c). After the adjustment phase, the participant's breath had been regulated into a slow and regular pattern. This stabilized phase might continue for a few minutes and be replaced by the phase of fatigue, where the amplitude decreased and the rate increased. We found that for most of the participants in graphic biofeedback sessions, e.g., Fig 9.8(a), this phase of fatigue came earlier and tended to be more apparent compared to the DeLight sessions, e.g., Fig 9.8(c).

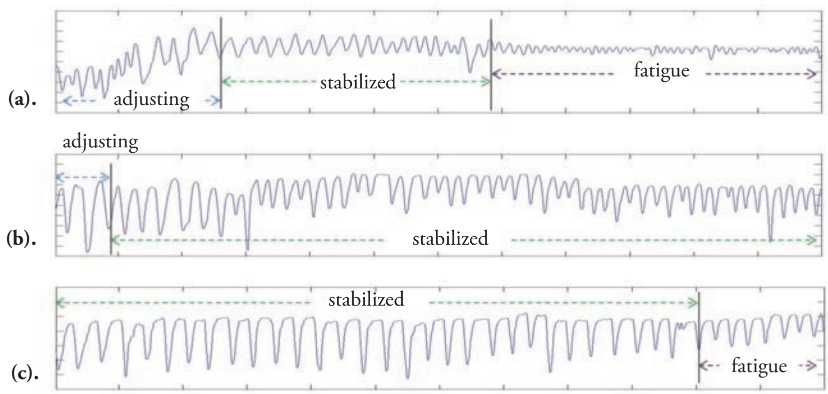


Fig 9.8 Typical breathing trace from the two participants (a). respiration of S4 with graphic biofeedback (b). respiration of S4 with DeLight (c). respiration of S13 with DeLight

9.4.2 Relaxation rating scale (RRS)

Fig 9.7(f) shows the relaxation ratings collected after each of the baseline, stress session, and two biofeedback sessions. There was a significant difference in RRS depending on the sessions ($X^2(3) = 43.03$, $p<0.01$). A Wilcoxon nonparametric test revealed that the relaxation ratings after the stress session (M=3.9, SD=1.89) was significantly lower than the baseline (M=6.85, SD=1.27, Z=−3.75, $p<0.01$). The RRS after the relaxation session with graphic biofeedback (M=5.16, SD=1.83) were improved significantly compared to the stress session (Z=−2.35, p=0.05), but still significantly lower than the baseline (Z=−2.98, $p<0.01$). The RRS after relaxation session with the DeLight biofeedback (M=7.53, SD=1.17) were significantly higher than the stress session (Z=−3.74, $p<0.01$), the graphic biofeedback session (Z=−3.75, $p<0.01$), and the baseline as well (Z=−2.54, $p<0.05$). These results suggest that biofeedback through ambient light might have led to more mental relaxation than GUI display.

9.5 Discussion and Conclusion

In this chapter, we developed a lighting biofeedback interface and compared it against a traditional graphic one. The experiment revealed that the biofeedback through both graphic and DeLight interfaces led to an increased HRV and reduced respiration rate. The results of the HRV and respiration rate are consistent with each other, supporting our hypothesis that the IBI biofeedback could help users in breathing regulation during a relaxation training to improve the heart rate variability. While the graphic interface and DeLight were comparable in the facilitation of deep breathing, DeLight led to a lower physiological arousal level (heart rate and SCRs) and a higher subjective relaxation rating (RRS). These results reveal the positive effects of lighting stimulus in enhancing physiological and mental relaxation.

In the experiment, we also recognized a 'relaxation-induced anxiety' appeared in some participants during graphic biofeedback sessions. 'Relaxation-induced anxiety' refers to new anxiety caused by relaxation training (Heide & Borkovec 1983). As shown in Fig 9.7 (a, b), the participants' HR and SCRs were increased in the relaxation session with graphic biofeedback compared to the resting baseline. The participants' relaxation ratings on the graphic BFB session was also significantly lower than the baseline. These results indicate an increased arousal (to some extent new anxiety) caused by the biofeedback technique. In contrast, in DeLight BFB session, this 'relaxation-induced anxiety' occurred rarely. The HR level was lower than the baseline. The SCRs was reduced to near the baseline. Moreover, the RRS was higher than the baseline. As such, we think the ambient light will be a proper medium for biofeedback display in everyday settings, which helps to minimize the relaxation-induced anxiety and makes the relaxation training a more casual practice rather than a severe task.

As documented by the systematic review in chapter 2, in the applications for stress management and relaxation training, more than half of the existing biofeedback systems rely on the screen-based visual display. In this chapter, as a new ambient interface, we see the potential of DeLight not only as an alternative information 'carrier' but also a 'booster' for relaxation. The user can get biofeedback information from surrounding environment and perform relaxation training with fewer restraints on the place of use. The combination of decorative and informative aspects makes the lighting interface both pleasant and helpful. Lighting displays are often combined with sound in multimodal interfaces to improve the capacity of the interface for information display or to enhance immersion and relaxation experience of the interaction (Vidyarthi et al. 2012; Adelbach et al. 2012). In the next chapter, we combine the DeLight with BioSoundscape, resulting in an audio-visual biofeedback system named RESonance, which aims to provide an immersive experience for biofeedback-assisted relaxation.

10

RESonance: Audio-visual Biofeedback for Immersive Relaxation Assistance

10.1 Introduction

The previous two chapters have presented the design and the evaluation of BioSoundscape and DeLight. We elaborated on how nature sounds and ambient lights were utilized for ambient biofeedback display. The effectiveness of these new interfaces for assisting self-regulation has been validated separately in each user experiment. These interfaces also featured in improved accessibility and an enhanced relaxation effect due to the positive stimuli from nature sounds and colored light. BioSoundscape can be 'nestled' among an indoor acoustic environment as a natural augment, both informing the user's internal states in the periphery of attention and also assisting relaxation training when it comes to the center of attention. DeLight can be seamlessly integrated into an indoor lighting environment, utilizing the distributed lights to facilitate a more casual relaxation practice. Moreover, we also found that many participants mentioned an experience of 'immersion' with both audio and lighting interfaces. These user feedbacks motivate us to combine the soundscape and 'light-scape' into a room-scale audio-visual biofeedback interface for an immersive relaxation training.

Many studies (Heide & Borkovec 1983; MacLean et al. 2013) have shown that the user experience with biofeedback techniques can be crucial to the effects of relaxation training. A meditative or an immersive experience may help users improve their engagement and facilitate a state of mindfulness. As such, the immersiveness was specifically addressed in some interactive systems for relaxation. For instance, *Sonic Cradle* (Vidyarthi et al. 2012) invites a user into a chamber of complete darkness and provides a meditative experience with a breath-based soundscape. *ExoBuilding* (Adelbach et al. 2012) harnesses lights, sounds and the shape changes of a physical space to present a user's physiological data and also shape an immersive experience for relaxation. A Virtual Reality (VR)-based interface can also enhance the user's immersion during a biofeedback training. For instance, *DEEP* (van Rooij et al. 2016) provides immersive breathing feedback through a VR game which situates players in a virtual underwater environment. The mindfulness training with *Inner-Garden* (Roo et al. 2017) seems more interactive and playful. It leverages a tangible artifact, spatial Augmented Reality, and VR headset to provide an engaging and immersive experience. However, such a biofeedback system typically has a high adaption threshold and deployment cost. Due to their specified requirements on spatial structure, new hardware, and operating configurations, it is relatively difficult to deploy these immersive biofeedback systems in everyday settings, e.g., a home or an office.

To strike a balance between engagement and ease of deployment for everyday settings, we present RESonance, a lightweight, room-scale audio-visual biofeedback system for immersive relaxation training. The system displays biofeedback data by using ambient mediums based on a lightweight infrastructure. RESonance harnesses ambient lights and nature soundscape to create a comforting and immersive environment that responds to the user's physiological data in real time. The design of RESonance also embodied the design principle of 'natural coupling' to offer a gentle-yet-intuitive representation of the physiological data. The two main contributions of this chapter are:

- Exploring a lightweight solution for immersive biofeedback that leverages ambient lights and nature soundscape to shape an engaging and relaxing user experience.
- Evaluating the system in a 24-participant user study.

10.2 Design and Implementation of RESonance

With RESonance, we explore an audio-visual biofeedback interface with ambient mediums that can be deployed in a living space or home environment seamlessly. The presentation mapping design of RESonance is mainly based on our previous work. Here we would like to stress three characteristics of RESonance as a lightweight, immersive, audio-visual biofeedback.

10.2.1 Immersiveness in simplicity

For everyday settings, RESonance is designed to meet the requirement of lightweight infrastructure and low deployment cost. RESonance harnesses ambient lights and a synthesized nature soundscape to turn a home or office into a biofeedback environment. The implementation of RESonance requires only 2-3 distributed 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 soft and diffused, filling the field of view. The setup of the lights can be adjusted to different room structure.

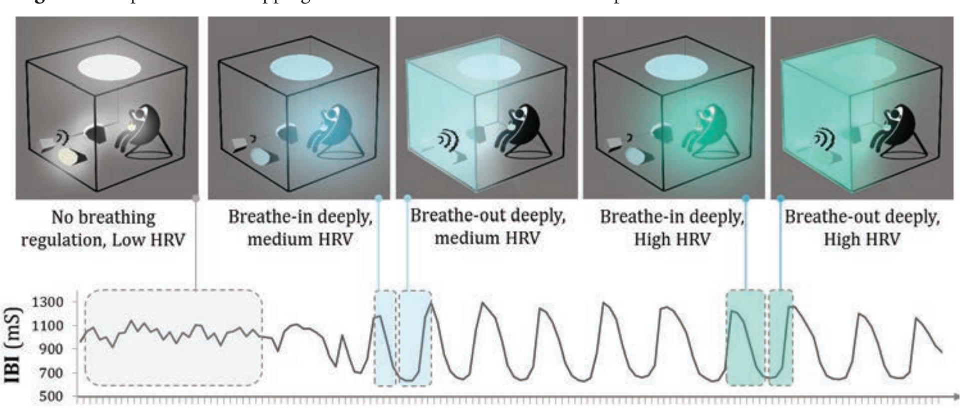
10.2.2 Inform through both center and periphery of attention

RESonance presents instantaneous IBI and short-term HRV (HRV_{16}) data. The feedback of IBI data aims to guide the users in respiration training. Moreover, the short-term HRV aims to inform the users about the training results. As playing a different role in relaxation training, the IBI and HRV data need different levels of the user's attention. RESonance works on the principle of Calm Technology (Weiser & Brown 1997), the IBI and HRV are distributed to the center and the periphery of the user's attention respectively. The IBI data are represented by the dynamic brightness transfer between the lights and the volume changes of the wind, which take the center of the attention for breathing guidance. In contrast, the HRV_{16} data is calculated based on a moving window and then coupled with the saturation of light color and the quietness of the soundscape. These changes can be perceived subtle and slow, so as to reside at the periphery of the user attention.

10.2.3 Natural coupling between the data and the interface expression

The presentation mapping in RESonance interface also follows the idea of 'natural coupling' suggested by (Djajadiningrat et al. 2002). The intention is to minimize cognitive workload and facilitate an intuitive interpretation of the interface expression. As shown in Fig 10.1, to represent IBI data for breathing training, the audio-visual expressions simulate the human's breathing movement. The lighting interface 'transfers' the brightness back and forth between the center and ambient lights and the audio interface modulates the wind volume. As the user breathes in, the brightness is transferred to the center light close to the body, and the wind in the soundscape becomes quiet. Conversely, when the user breathes out, the brightness is transferred to the ambient lights far from the body, the wind becomes loud.

Fig 10.1 The presentation mapping between the RESonance interface expressions to the IBI data



As a cool-toned light is commonly associated with a sense of calmness, we use a blue-green color to indicate an improved HRV. When the user achieves a better relaxation with an improved HRV, the lights will turn to be a more saturated blue-green, see Fig 10.2. The quietness of the soundscape could be naturally associated with a peaceful and relaxed state of the body. Thereby, in the audio interface, we use the quietness changes to represent the HRV level, in this way, an improved HRV will drive the nature soundscape to become quiet and simple.

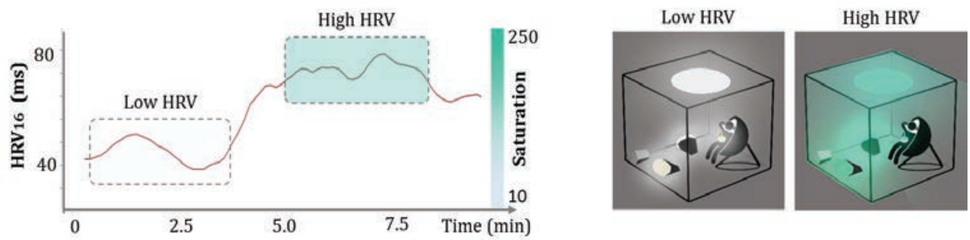


Fig 10.2 The presentation mapping between the saturation of light color to the HRV data

10.2.4 System implementation

Fig 10.3 shows the framework of RESonance HRV biofeedback system. The BVP signal is measured by a PPG sensor on the user's finger. In the biofeedback program, the BVP signal is processed into IBI and HRV data which are further coupled with the audio and lighting parameters. RESonance biofeedback program is implemented on the *Processing* platform. The lighting system includes a set of programmable light bulbs produced under the *HUE* brand by *Philips*. In the sound synthesis procedure, the biofeedback data modulate the parameters of the audio contents in an NS library with *Beads* Java audio library. For a detailed description of the presentation mapping, see chapter 8, section 8.3 and chapter 9, section 9.2.

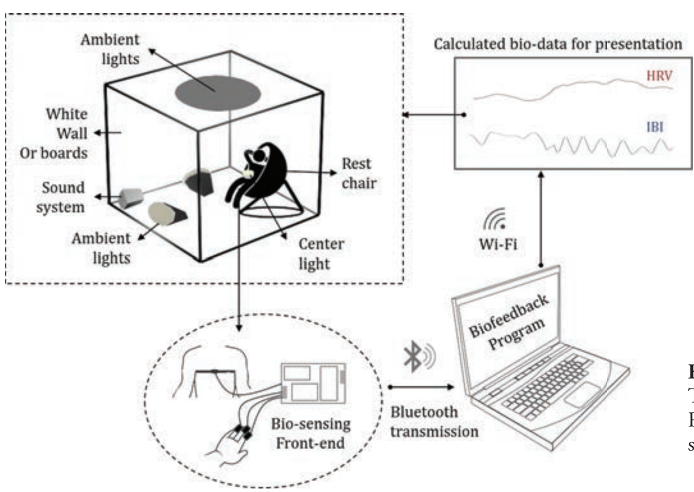


Fig 10.3
The framework of RESonance biofeedback system

10.3 Evaluation

The user study aimed to evaluate the effectiveness of RESonance biofeedback system for relaxation assistance. We used a within-subjects repeated measures design with each participant experiencing resting, stress and relaxation training. In the experiment, the participants underwent a stress induction task before the relaxation training using RESonance. The experiment hypothesized that the relaxation with RESonance system could help the users to reduce the physiological arousal, facilitate deep breathing and enhance heart rate variability. Meanwhile, we also investigated the user experience with the audio-visual display by collecting and analyzing the quantitative data of follow-up interviews.

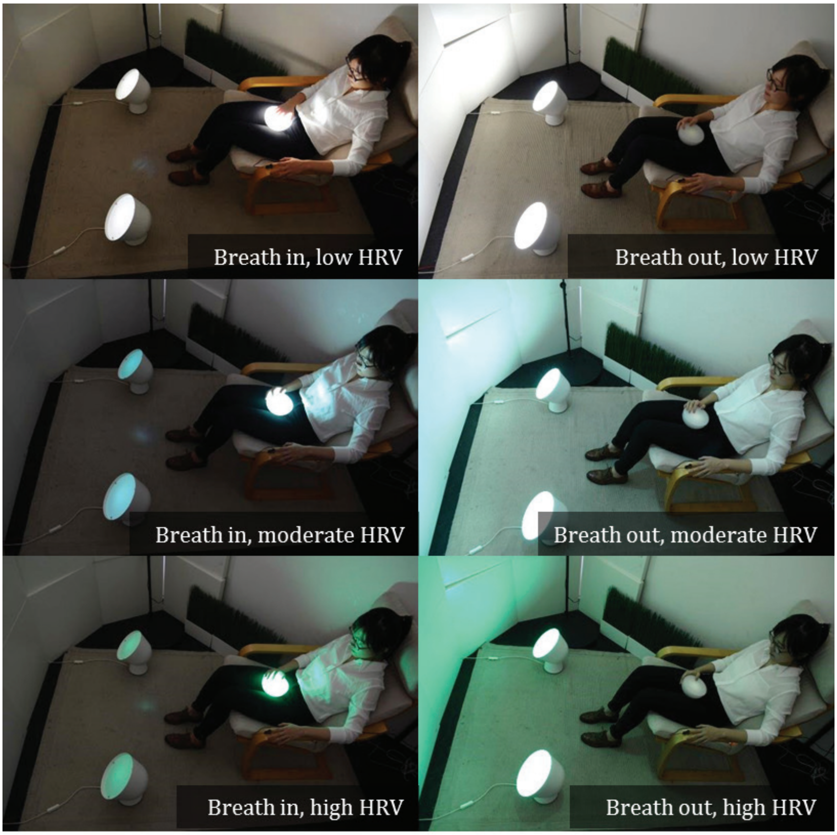


Fig 10.4
A user performing relaxation training with RESonance biofeedback system

10.3.1 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 subjects gave the written informed consent.

10.3.2 Setting up

A lab space was designed to simulate a home environment for setting up the 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, the bio-sensing device, three lights and a sound speaker. The wireless speaker is placed behind the whiteboard in front of the chair. 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.

10.3.3 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 to the participants first. 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 psychophysiological stress responses. Before the stage 3, the participant experienced a short trial of RESonance system. In stage 3, the participant performed relaxation training with the HRV biofeedback through RESonance. For each stage, we collected the participant's physiological data and the self-reports on anxiety and relaxation. At the end of the study, we conducted a follow-up interview to collect qualitative data about user experience.

10.3.4 Simulated stressors

In the experiment, we combined a Stroop color-word test (Prinsloo et al. 2011) and a mental arithmetic test (Whited et al. 2014) as an acute time-limited stressor to induce the stress responses of the participants. Only when the participants passed the Stroop test, they can start the arithmetic test. In the arithmetic test, the participants were required to get a higher score as quickly as possible. The whole stress session (in stage 2) lasted 10 minutes.

10.3.5 Biofeedback protocol

In stage 3, the participants relaxed with biofeedback. The working of RESonance biofeedback system was introduced and explained beforehand 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 lights will be getting closer to blue-green and nature soundscape will be getting quiet and simple*".

10.3.6 Measurements and data analysis

The physiological measures include skin conductance responses (SCRs), respiration rate (RSP-R) and the index of heart rate variability (HRV-LF%). These physiological data were recorded in all three stages. After each stage, we collected the participant's self-report on anxiety and relaxation experience by Relaxation Rating Scale (RRS) and State-Trait Anxiety Inventory (STAI), refer to the more details in chapter 8, section 8.4.3. At the conclusion of the experiment, a semi-structured interview was conducted to collect the qualitative data regarding the user experience and their opinions on the room-scale audio-visual interface. The interview focused on three themes with a pre-determined set of open questions as listed in Table 10.1. 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 10.1. The list of questions for the interview

Theme	No.	Interview Questions
Room scale interface	Q1 Q2	*What did you (not) like 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?*

10.4 Quantitative Results

Table 10.2 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 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.

Condition		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

Table 10.2 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).

10.4.1 RESonance biofeedback reduces physiological arousal

The SCRs value can indicate the physiological arousal and stress level of participants. Fig 10.5(a) shows the changes in SCRs during the stress stage and biofeedback relaxation stage (relative to the baseline measurements). Due to the stressful task, most participants showed an increase in SCRs compared to their baseline measures. During the biofeedback stage, for most participants, their SCRs were reduced, lower than the stress stage and 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 relaxation stage (Mdn=2.85, SD=1.96) and the stress stage (Mdn=7.80, SD=2.46). The results are suggestive that the immersion in the ambient lighting and soundscape environment created by the RESonance system could efficiently reduce the physiological arousal to a low level.

10.4.2 RESonance biofeedback facilitates deep breathing

Fig 10.6 shows the changes in respiration rate (RSP-R) during the stress stage and biofeedback relaxation stage (relative to the baseline measurements). During the biofeedback relaxation, the RSP-R dropped significantly lower than the stress stage and the baseline stage. A Wilcoxon Signed-rank test shows that the respiration rate was significantly reduced in biofeedback stage (Mdn=6.66, SD=3.4), compared to 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 show that the RESonance system is useful in facilitating the deep breathing during the relaxation training.

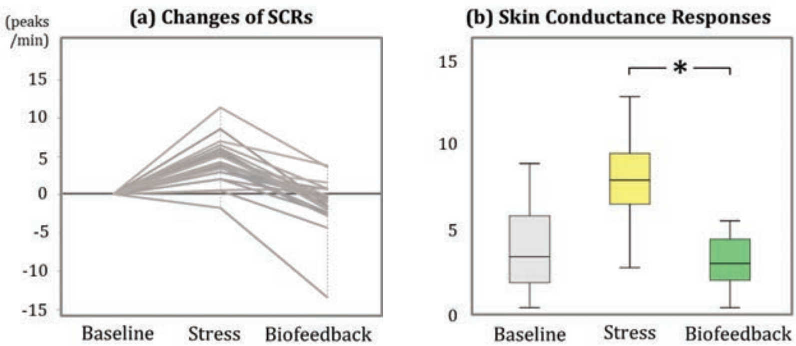


Fig 10.5
The SCRs changes and the boxplots for three stages

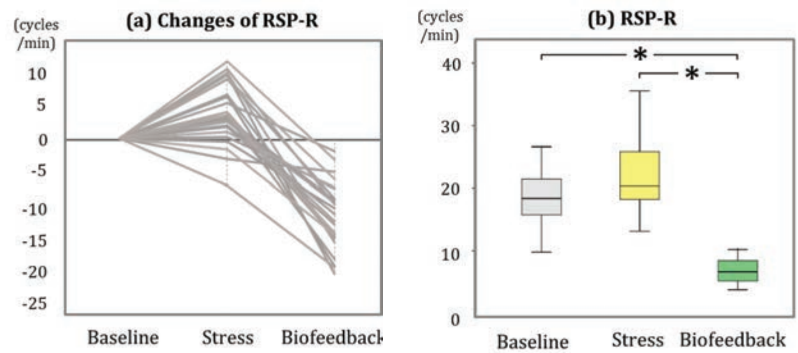


Fig 10.6
The RSP-R changes and the boxplots for three stages

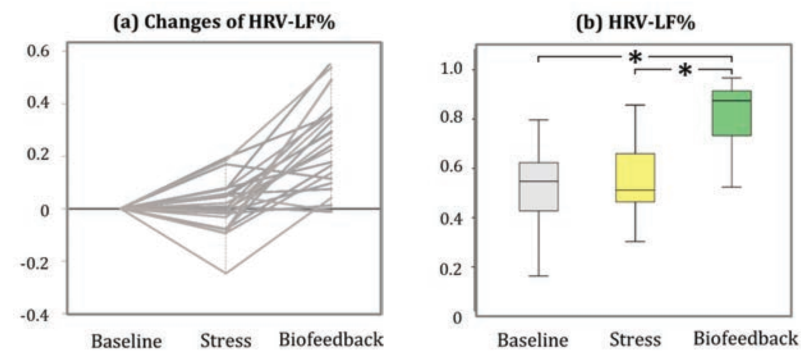


Fig 10.7
The HRV changes and the boxplots for three stages

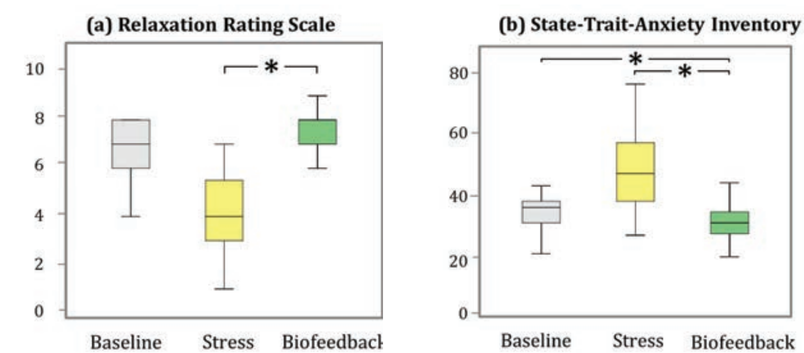


Fig 10.8
The Boxplots of the STAI and RRS results

10.4.3 RESonance biofeedback enhances heart rate variability

Fig 10.7 shows that the changes in HRV-LF% during the stress stage and biofeedback relaxation (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 (Lehrer et al. 2000). Especially when the user achieves her/his 'resonant' breathing around 10s per cycle, the power spectrum of LF band will increase significantly around 0.1Hz. The results of the HRV are consistent with the respiration results, indicating that the RESonance helps the user to regulate the respiration into an optimal pattern (i.e., resonant breathing).

10.4.4 RESonance biofeedback reduces subjective anxiety

Regarding the State-Trait Anxiety Inventory (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). Regarding the Relaxation Rating Scale (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). The self-reports data confirmed that the lights and sound stimuli of the RESonance could help the users relax mentally.

10.5 Interview Results about User Experience

10.5.1 Theme 1: relaxing ambience created by RESonance

The responses indicated that the room-scale RESonance interface could provide a relaxing and immersive experience. 14 participants (out of 24) mentioned that the 'semi-enclosed' space of the RESonance space helped them concentrate during the relaxation training. 22/24 stated that the blue-green colored 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).

10.5.2 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 lights were easy to perceive. 20/24 stated that the IBI feedback provided by spatial 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).

10.5.3 Theme 3: Nature soundscape and its user experience

Regarding the audio display, the responses indicated that the quietness of the nature soundscape could effectively present the results of the training, 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 the quietness was easy to identify through the loudness and frequency of birds or the loudness of water. 23/24 thought the created nature soundscape was relaxing and pleasant. 13/24 mentioned 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.

10.6 Discussion

10.6.1 A lightweight design for immersive relaxation training

We think RESonance can be a complement to the current immersive biofeedback designs that are mostly based on an adaptive architecture (Vidyarthi et al. 2012; Adelbach et al. 2012) or a head-mounted VR device (van Rooij et al. 2016; Roo et al. 2017). Without using a VR device and or a functional space, 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 IoT techniques, a future 'smart home' might offer increasing ambient mediums to inform and interact with its inhabitants. We think RESonance can easily blend into a real home in the future based on a wide range of intelligent lights (e.g., *Philips Hue*) and intelligent speakers (e.g., *Google Home*, *Apple HomePod*, *Amazon Echo*). A smart home speaker can fill the room with immersive 360° audio and provide an augmented soundscape. An intelligent lighting system may color the home, lounge room and even office, turning it into an immersive luminous space.

10.6.2 Natural coupling embraces somaesthetic appreciation

Based on the responses from the interviews, we found that the set-up of RESonance system in the experiment embraced some qualities of '*Somaesthetic Appreciation Design*' proposed by Höök et al. (2016). Firstly, they suggested "*making space*" to create an atmosphere as well as to block out disturbances. As Höök phrases that "*it became important to build a secluded space, forming a certain atmosphere or feeling safe, enclosed, taken care of.*" In our set-up, we constructed a semi-enclosed space as the relaxation space. Besides the physical space, the spatial lights further sculpted and reinforced the space. The participants also reported that the semi-enclosed space helped them reduce distractions and concentrate on their breathing. Secondly, the quality of '*subtle guidance*' was manifested in the lighting interface where the IBI data is presented by the 'transfer' of brightness between the center light and ambient lights. The expression of lights mirrors the user's breathing movement, making the feedback meaningful and intuitively understandable. We set the lights in different distances to the user. The center light was held by the user in hands near the body, while the ambient lights were placed at a distance. When the user inhaled air into the body, the light seemed 'attracted' to the body. And when the user breathes out, the light 'spread out'. This design aimed to build an intimate relationship between the light and the user, reinforcing the experience of changing between inhaling and exhaling.

10.6.3 Multiple modalities enhance the information perception

Many researchers suggest that multimodal feedback may reduce the cognitive load and enhance the perception in a learning process due to a distribution of information processing (Burke et al. 2006). For instance, in a complex task, different information can be presented in visual and audio channels separately. However, in the relaxation training, the self-regulation task (e.g., deep breathing) and the physiological data (e.g., IBI and HRV) for feedback can be very simple. Hence, in the design of RESonance, the data are presented in both lighting and audio interfaces. The responses from the users 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.

10.6.4 Designing the sensory stimulus in the user interface

The interactive media used in the interface design will be a potential stimulus to mediate user experience and enhance relaxation. The external signals from the interface might either promote relaxation or induce an anxiety we expect least. We suggest carefully selecting and modulating the interactive media for a relaxing experience. In our design, a cool-toned light was selected due to its ability to create a feeling of calm and reduce arousals (Ross et al. 2013). The color is modulated by the parameter of saturation instead of the hue. In this way, the light can be perceived as a consistent cool-toned color. Instead of transforming the biofeedback data directly into an audio tone or a melody, we harnessed some well-proven nature sounds to shape an acoustic natural environment as a positive stimulus for relaxation. According to Benfield et al. (2014) and Alvarsson et al. (2010), we selected the birds singing and the murmur of a brook because they may comfort an individual's mind and foster the experience of calmness and relaxation. Moreover, regarding the modulation of the sounds, we applied the developed NS model for a calm experience. In addition, many interactive media can also 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.

10.7 Conclusion

In this chapter, we have presented a room-scale audio-visual biofeedback system for immersive relaxation training. The system presents IBI and HRV data through the ambient lights and a nature soundscape in a room. The experiment has compared the participant's physiological measures and self-report data under three stages: resting baseline, stressful task, and biofeedback-assisted relaxation. The quantitative results suggest that the system could effectively support relaxation training by reducing the arousal level, slowing the breath, and enhancing the heart rate variability. The results of the interview reveal that the ambience created by the lights and nature sounds could shape an immersive and engaging experience. Through this study, we can also see the potential of RESonance not only for relaxation training but also for informing the users and promote their behavior changes by combining with the persuasive technology. In this light, the findings of this study are a starting point for further studies on a physiologically driven smart home environment for better health and wellbeing.

The biofeedback technique and the RESonance interface are new to most users. As described in chapter 2, biofeedback-assisted relaxation training is a learning process. It may require more practices to familiarize the users with the interface and build the relationship between the external displays and their internal physiological processes. In the next chapter, we evaluate the RESonance as a biofeedback-training tool in a multi-session biofeedback training program and investigate the effectiveness of the biofeedback system for the acquisition of self-regulation skills.

11

Investigating the Effects of Multi-Session Biofeedback Training on Stress Management

11.1 Introduction

In chapters 8-10, biofeedback was used for assisting relaxation training. We evaluated these biofeedback designs, BioSoundscape, DeLight, and RESonance regarding their usability and user experience in a relaxation training. These previous studies have shown that the biofeedback systems could efficiently facilitate breathing regulation and stress relief. On the other hand, biofeedback can also assist users in learning specialized mind/body skills to cope with stress. Just like learning to play the piano or tennis, the biofeedback-assisted learning process also requires practice. Through the practice, the users become familiar with the biofeedback displays, build the relationship between the feedback and their self-regulation behaviors, and learn to control specific physiological activities to a healthy direction. To investigate the effectiveness of biofeedback in the assistance of skills learning, it was necessary to conduct a new user study with a multi-session biofeedback training program. In this chapter, we present the evaluation of RESonance biofeedback system in a multi-session training program for two different groups of users: soccer players and academic researchers.

In general, stress can be classified into two types: acute stress and chronic stress. Due to the characteristic of work, the stresses encountered by soccer players and academic researchers are quite different. Soccer players are frequently exposed to high-pressure events and acute stressors, while the stress of academic researchers tends to be chronic, prolonged, and encountered on a daily basis. This study recruited five academic researchers (Ph.D. employees) and five soccer players into a relaxation training program of four training trials that use RESonance audio-visual biofeedback system regularly. The participants were instructed to practice the biofeedback-assisted relaxation training to cope with induced stress. We compared the participants' psychological and physiological responses towards a simulated stressor before and after the multi-session biofeedback training program. Besides, we also investigated the learning curves of biofeedback by analyzing the self-regulation performance along with the time of training.

11.2 Related Work

An excessive amount of stress is often debilitating to an athlete's sports performance. Before a match, an overstressed state of athletes may result in various emotional problems, such as loss of composure, aggression, anger, regression or fear (Neil et al. 2011). Severe stress may also cause physical problems such as nausea, muscle tension (Lundberg et al. 1994), reduced motor coordination, lack of focus, and insomnia (Morin et al. 2003). During the match, only when the players are alert but relaxed, they can make better, quicker decisions during a match. A high-tension state may put them at high risk of injury due to decreased response time and disorientated attention level. Relaxation training before the match may help prepare the players for enormous pressure and distractions. Various mental training and relaxation strategies have been used to deal with competitive stress, helping the soccer players to reach an ideal performance state of 'relaxed readiness'. These relaxation techniques include autogenic training, meditation, diaphragmatic breathing, visualization and music listening. Besides reducing tension, a regular mental training program also aims to improve players' skills on self-regulation of arousal and empower them to adjust and maintain an appropriate arousal level.

Several studies have supported that biofeedback can be a useful tool in helping an athlete learn to control arousal level, manage emotions and mood swings and ultimately achieve physiological readiness of the body for optimum performance. For instance, a regular biofeedback intervention has the potential to reduce injury risk in junior football players (Edvardsson et al. 2012). A 10-days HRV biofeedback training helped the basketball players lower the anxiety and find their 'zone of excellence' (Paul & Garg 2012). An 8-week-long biofeedback training could effectively help the athletes to improve the psychophysiological control over competitive anxiety and enhance athletic performance (Pusenjak et al. 2015). Another example in soccer training is the 'Mind Room' used by the Italian soccer team. After the Italian team's success in winning the 2006 World Cup, it was reported that some of the players have trained in the Mind Room with a biofeedback device to enhance their relaxation and improve self-regulation skills on arousal and stress (Vietta et al. 2006).

11.3 Methods

11.3.1 Participants

Five male soccer players ranging in age from 16 to 18 years were recruited from *Philips Sports Vereniging* (PSV) football sports club, Eindhoven. Five Ph.D. researchers (two males and three females) ranging in age from 27 to 29 years were recruited from Industrial Design Department, Eindhoven University of Technology, TU/e. All participants have never received any medical HRV biofeedback training. All participants gave the written informed consent and provided the permission for publication of photographs with a scientific and educational purpose.

11.3.2 Study design

The study was carried out with the Ph.D. students in the university and with the soccer players at the training facilities. The set-up of the RESonance system was adjusted according to the facilities. The simulated stressors used in the training program were adapted to the participant group. The use of biofeedback system, procedures, measures, and analysis approaches are same for both groups of the participants. The timeline for the study and the procedure of each experimental trial are shown in Fig 11.1.

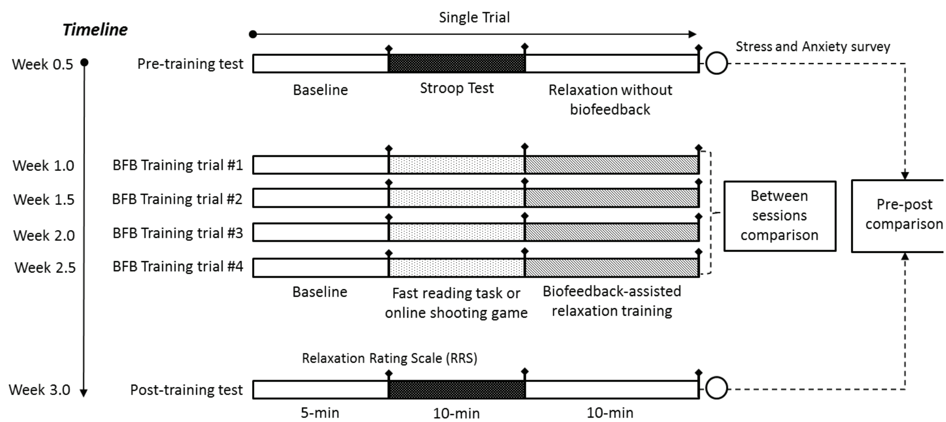


Fig 11.1 The timeline of the study and the procedure of each trial

The study lasted for three weeks and consisted of six trials: a pre-training test, a post-training test and four biofeedback training trials. All participants underwent a pre-training test before the start of their training trials and a post-training test afterward. We compared the measurements between the pre- and post-training tests to evaluate the effects of multi-session biofeedback training program. The pre-post comparisons examine whether the participants can improve their resistibility to the stressors and the self-regulation skills to recover from stress quickly. The biofeedback trials were performed twice per week, for two weeks. The participants practiced the breathing skills to improve the heart rate variability with RESonance HRV biofeedback system. The measures for each training trial were also recorded to investigate the learning curves of biofeedback technique.

11.3.3 Procedure

The procedure for the pre- and post-training test consisted of three sessions. On arrival at the RESonance mind room, the participant was attached with bio-sensors to measure blood volume pulse (BVP), respiration (RSP) and skin conductance

(SC). In the first session, the participant was seated quietly for baseline collection. In the second session, the participant was asked to perform a 10-minute stressful task for inducing the psychophysiological stress responses. In the third session, the participant relaxed for 10 minutes without biofeedback. For the pre-training and post-training tests, we used the Stroop color-word test as the mentally challenging task for all the participants to induce stress responses.

The procedure for biofeedback training trials also consisted of three sessions: a 5-minute resting session, a 10-minute stress-induction session, and a 10-minute biofeedback relaxation training session. Different from pre- and post-training tests, here the participants would relax with the assistance of biofeedback during the relaxation sessions. The stress-induction sessions were designed to simulate the work-related stress. Given different groups of participants, we selected different stress-induction procedures for Ph.D. students and soccer players.

The Ph.D. students were required to complete a fast-reading task in 10 minutes. The fast-reading task serves as a time-limited stressor which is very common for academic staff in daily work. The students were required to read an academic article fast and find the key information to complete a summary. During the task, they were exposed to a soundscape of a busy office. It includes the sounds of printing, phone ringing, typing, and chatting. The soccer players were required to play an online shooting game against the computer for 10 minutes. The game simulates a penalty shootout in a soccer match which is one of the most stressful experiences for most soccer players. The players switch roles between the goalkeeper and goal kicker to help the selected team to win. The game provides a soundscape of the soccer field during a match.

11.3.4 Set-up of RESonance biofeedback mind room for relaxation training

The mind-room was equipped with the same RESonance biofeedback system described and validated in the previous chapter. For the Ph.D. students, the study was carried out with the RESonance system installed in an individual office room (see chapter 10). For the soccer players, a new mind room was built at the training facilities. As shown in Fig 11.2(a), a biofeedback mind room has been set up in a container placed in the training facilities. The space of the container is divided into two functional areas: the stress-inducing working area and the biofeedback mind room. The mind room space was constructed by a white jersey fabric stretched over a cube-shaped wooden frame (2.5m × 2.5m). Within the mind-room space, there are an armchair, a bio-sensing device, and the center light. The ambient lights are installed outside of the space and shine the light on the fabrics, see Fig 11.2(b). The center light is a wireless and portable lamp which is in the sight of the user and can also be held during the relaxation. The ambient lights aim to create an immersive lighting environment. Four speakers from a surrounding sound system are installed around the space to create a virtual surround-sound effects of a nature soundscape.

Fig 11.2
Set up of RESonance Mind Room (a) located at training facilities (b) cube-shaped mind room space

The RESonance Mind-Room has been set up in the container placed in the De Herdgang facilities.

The Mind Room provides football players an relaxing environment for biofeedback training.

Fig 11.3
the players perform relaxation training in the Mind Room

11.3.5 Measurements

For the pre- and post-training tests, we measure the participants' self-report on stress/anxiety level by Relaxation Rating Scale (RRS) and the State-Trait-Anxiety-Inventory (STAI) questionnaires. During the pre- and post- and all biofeedback training sessions, the participants' skin conductance responses (SCRs), respiration rate (RSP-R), heart rate variability (HRV-SDNN) are measured using a Nexus-10 device and stored individually in the program (see the details in chapter 8).

11.3.6 Data analysis

Between the pre-training and post-training tests, the comparison of self-report psychological data was analyzed by using Wilcoxon signed-rank test and a paired-samples t-test was conducted to compare physiological measures. All parametric data are described as the mean ± standard deviation (*SD*) and nonparametric data as a median and interquartile range (IQR). A p value of <0.05 was considered to be statistically significant. p values larger than 0.05 but approaching significance are reported as exact values.

11.4 Effects of Multi-Session Biofeedback Relaxation Training

11.4.1 Physiological data

As shown in Fig 11.4, in both pre- and post-training tests, the SCRs were decreased significantly during the relaxation session compared to the stress session ($p<0.05$). After four biofeedback training trials, the participants show a relatively larger decrease in SCRs, pre-training (−2.92±3.82) and post-training (−3.52±2.94), which suggests that the biofeedback training has the potential to enhance the user's skills to moderate the increased arousal after the stressful tasks. However, the difference in the SCRs changes between pre-training and post-training tests was not significant; $t(9)=0.502$, $p=0.628$.

As shown in Fig 11.5, in both pre- and post-training tests, the respiration rate was significantly reduced during the relaxation session compared to the stress session ($p<0.05$). In the post-training test, more participants (n=8) maintained relatively slow respiration in stress session, and all the participants showed a large decrease in respiration rate in relaxation session. The respiration rate decreased more significantly in the post-training test (−10.86±7.5) than in pre-training test (−5.77±4.77). The difference is not significant based on paired-samples t-test, $t(9)=2.24$, $p=0.05$. The result suggests that the multiple sessions of HRV biofeedback training can be effective in improving the breathing skills to achieve a deep and smooth breathing pattern.

As shown in Fig 11.6, in the pre-training test, there was no significant difference in HRV between stress session (55.64±17.87) and relaxation session (62.19±18.28); p=0.189. After the biofeedback training, the HRV was significantly improved in relaxation session (67.18±23.99) higher than the stress session (84.29±30.41); p<0.05. The improvements of HRV in the post-training trial (17.11±17.1) is higher than the pre-training trial (6.55±14.59); however, the difference was not significant; $t(9)$=-1.78, p=0.108.

11.4.2 Self-report survey data

As shown in Fig 11.7, in both pre- and post-training tests, the participants reported a significantly reduced relaxation level for stress session (p<0.05). Moreover, after the relaxation session, the RRS was improved significantly (p<0.05) and returned close to the baseline level. A Wilcoxon test showed that the 2-weeks biofeedback training did not elicit a significantly larger improvement in RRS (Z=−0.07, p=0.943). Also, compared to the Ph.D. students, the soccer players reported a higher baseline and smaller changes of RRS in different sessions.

As shown in Fig 11.8, in both pre- and post-training tests, the participants reported a significantly higher anxiety level on STAI in the stress session (p<0.05). Moreover, after the relaxation session, the anxiety level was significantly reduced (p<0.05) close to the baseline level. A Wilcoxon test showed that the biofeedback training did not elicit a significantly larger decrease in STAI anxiety reports (Z=−0.05, p=0.959).

Moreover, we found that it was difficult to simulate an effective stressor for the soccer players. The psychological effects of the Stroop color-word test or the online penalty shootout game were not evident on the players. As shown in Fig 11.7(a), the baseline of relaxation rating for the players were relatively high and changed little in stress or relaxation session. Fig 11.8(a) reflects a similar trend in anxiety self-report.

In a follow-up interview, the soccer players reported that the lab-based stress-inducing tasks were likely to be a fun game instead of a serious stressor. They also stated that, in most cases, their stress is closely linked to their expectation for competition, their latest performances and fitness, and the responses of the audience. For instance, some participants listed some typical stressful conditions: waiting for the first round name list before the match, waiting on the bench during the match or made some misplays or an infraction of the rules. Typically, these stress are short, event-based, but serious and massive. Besides the mentally challenging tasks, various new procedures are proposed to induce stress, such Trier Social Stress Test (Kirschbaum et al. 1993), public speaking, and group interview. Still, these general procedures might not induce the stress reliably for specialized occupations, such as soccer players. A more tailored stress induction procedure is required.

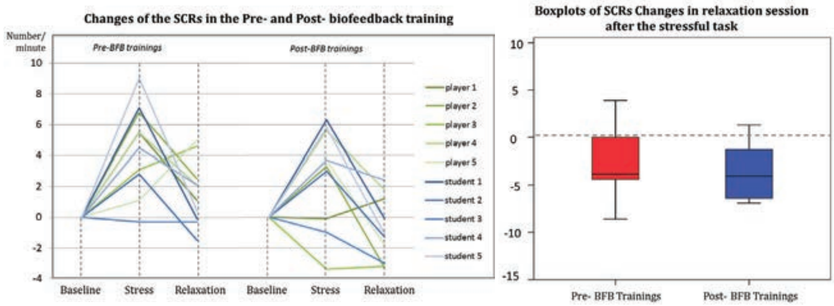


Fig 11.4
The results of SCRs changes between stress and relaxation sessions for pre-training and post-training tests

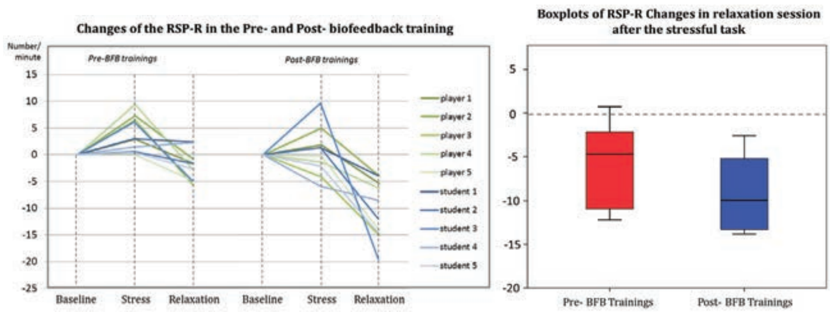


Fig 11.5
The results of RSP-R changes between stress and relaxation sessions for pre-training and post-training tests

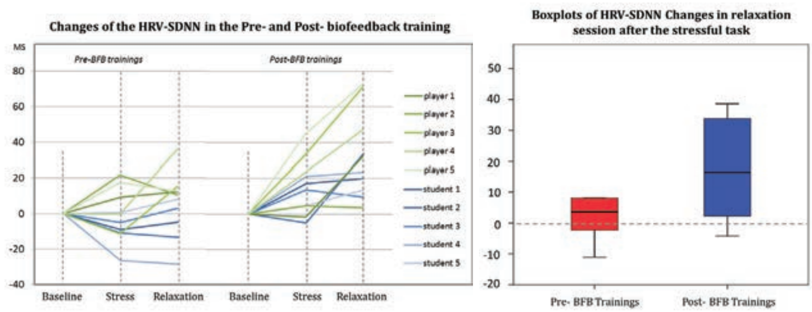


Fig 11.6
The results of HRV changes between stress and relaxation sessions for pre-training and post-training tests

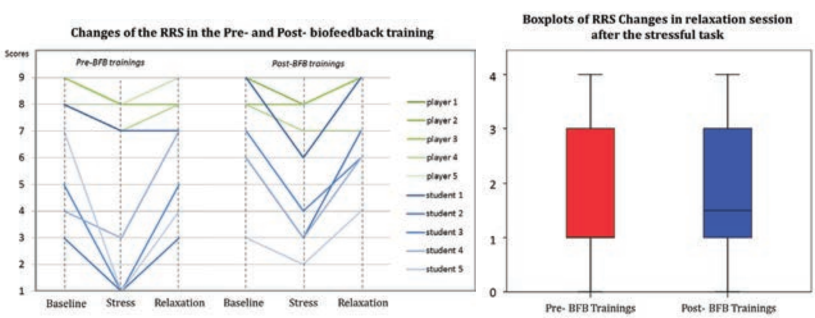


Fig 11.7
The results of RRS changes between stress and relax-ation sessions for pre-training and post-training tests

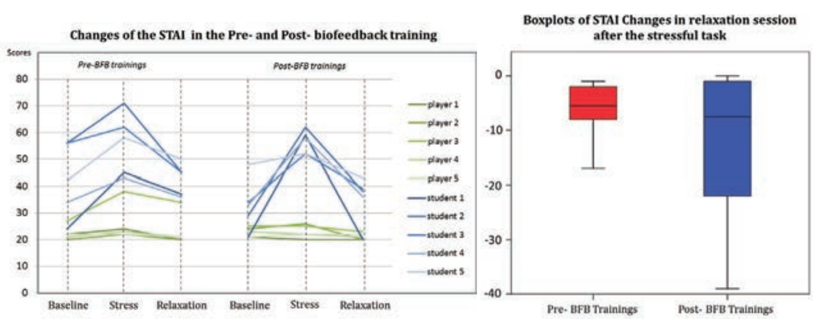


Fig 11.8
The results of STAI changes between stress and relaxation sessions for pre-training and post-training tests

11.5 Skills Learning with Biofeedback

11.5.1 Learning curve for biofeedback training

In the relaxation training, the HRV biofeedback system assists the users to regulate their breathing into a slow and deep pattern and further achieve their 'resonant breathing', at which the spectral powers in low frequency (LF) ranges of heart rate variability will be greatly enhanced. Therefore, we calculated the average respiration rate as a performance index of biofeedback training and the HRV-LF% as an index of the training results.

As shown in Fig 11.9(b), the average respiration cycle for all participants showed steady improvement over time. The average increase in respiration cycles between two consecutive training trials for all participants was 7.14%. The average respiration cycle in training trials #1 and #4 were 7.64±3.42 (SD) and 9.39±1.86 seconds respectively. The percentage of improvement between the two was 22.97%. The standard deviation decreased along with the training trials.

In the student group, the average respiration cycle in trial #1 and #4 was 6.99±2.13 and 9.81±1.68 seconds respectively. In the player group, the average respiration cycle in trial #1 and #4 was 8.28±4.56 and 9.97±2.13 seconds respectively. As shown in Fig 11.9(a), three players started with a quite long respiration cycle, their respiration cycles remained stable around 10 seconds per cycle in the rest three training trials. For the other two players, their learning curves showed a steady rising trend along with the trials. The performance of the students was different and unsteady in the first three trials. However, the learning curve demonstrated a significant improvement in the fourth trial where the respiration cycle has been improved close to 10 seconds.

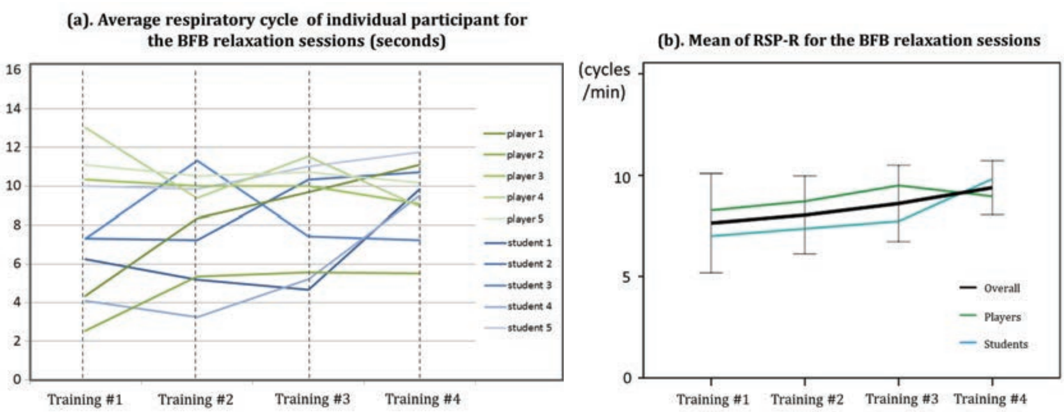


Fig 11.9 The learning curve regarding the performance (respiration regulation) along with training

Regarding the HRV, both the student group and the player group showed steady improvement along with the biofeedback training, see Fig 11.10(b). As the index of self-regulation results, an improved HRV-LF% may indicate a successful biofeedback relaxation training. The average HRV-LF% in trial #1 and #4 was 60.2±22.8 and 82.9±11.1 respectively. A comparison between the trial #1 and #4 demonstrated a statistically significant improvement, $p<0.05$. The percentage of improvement in HRV-LF% for all participants was 35.5%.

In the player group, the average HRV-LF% in trial #1 and #4 was 51.9±25.6 and 86.3±10.5 respectively. As shown in Fig 11.10(a), the HRV-LF% results of four players were relatively stable and remained at a high level (≥75%). In the student group, the average HRV-LF% in trial #1 and #4 was 68.46±18.64 and 79.5±11.7 respectively. Compared to the player group, the HRV-LF% of the students fluctuated largely.

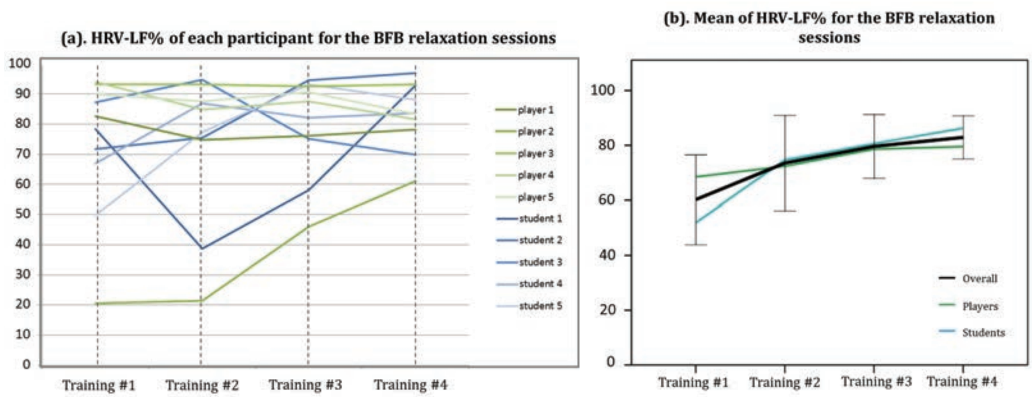


Fig 11.10 The learning curve regarding the results (HRV-LF%) along with biofeedback training

11.5.2 Time-frequency power spectrum

The above learning curves show the overall improvement of the performance and the results along with the biofeedback training. In this section, we present a sequence of time-frequency power spectrum plots to reveal more details about the self-regulation process in each trial. The time-frequency power spectrum plot could demonstrate the time related spectral components of HRV. Fig 11.11 shows a group of typical time-frequency power spectrum plots in the baseline session, stress session, and biofeedback-assisted relaxation session. We can see the changes in spectral components among different sessions.

As shown in Fig 11.11(b), during a stressful task, there are apparent spectral powers in high frequency (HF) ranges from the 0.15 to 0.4 Hz. During a short-term biofeedback relaxation session (c), the biofeedback information helps the user to regulate breathing pattern and achieve a lower breathing rate, which enhances the spectral powers in low frequency (LF) ranges from 0.05-0.15 Hz. Especially, when the user performs the 'resonant breathing', the LF powers burst at around 0.1 Hz (Schipke et al. 1998). Here, we use the LF powers in power spectrum plots as an index of the breathing regulation performance. The visual interpretation of the time-frequency power spectrum plots may qualitatively reflect the biofeedback learning process along with the training trials.

Fig 11.12 shows the power spectrum plots of four training trials for each participant. Compared to Fig 11.11(a) and (b), most plots showed enhanced spectral power in low frequency below 0.15 Hz. However, it usually takes a different amount of time and efforts to learn the self-regulation skills for different participants. From the power spectrum plots, the participants showed two different learning process. For P2, P3, P4, P5, P8, and P9, they could quickly harness the biofeedback in self-learning of the 'resonant breathing' at the first training trial. However, for these 'quick' learners, their performance was not improved along with the biofeedback training but had its ups and downs within a range at a relatively good level. For P1, P6, P7, and P10, there was a continuous learning process reflected by the power spectrum plots. They performed at their best in the last trial. Their performance was not satisfactory in their first trial but steadily improved along with the training.

11.6 Discussion

The effectiveness of biofeedback training in stress management has been demonstrated in several studies (for a review, see chapter 2). This chapter focused on the evaluation of a newly-developed RESonance biofeedback system in a multi-session training program. Generally speaking, biofeedback-assisted training is a learning process for acquiring specialized mind-body skills, in which the biofeedback device/system acts as a 'crutch' to facilitate the skill learning. Based on a long-term training program, the users are expected to acquire specific self-regulation skills and use them easily without the extra biofeedback equipment. In this chapter, we examined whether a multi-session biofeedback training program could equip users with better skills to cope with stress. We compared the SCRs, RSP-R, HRV, RRS and STAI data measured in a relaxation session without biofeedback, before and after four biofeedback training sessions. The results of the pre-post comparison were promising and suggested that the biofeedback training resulted in a slower respiration rate and higher heart rate variability during the relaxation.

The study also preliminarily investigated the user's learning curve with biofeedback. A biofeedback-assisted relaxation training may require time to familiarize the users with the biofeedback system. The user can learn by trial and error to adjust their bodily or mental processes, and behavior (behavior conditioning) to control specific physiological processes towards an expected direction. Finally, it will still take a lot of practice for the users to internalize these skills of self-regulation and use them in their everyday life to cope with stress. Each of these processes may take different time and efforts for different individuals. This study involved two

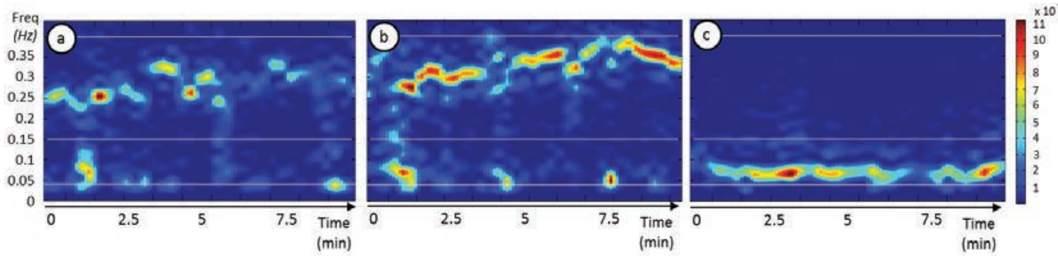


Fig 11.11. A group of typical time-frequency power spectrum plots in the (a) baseline session (b) stress session and (c) biofeedback-assisted relaxation session.

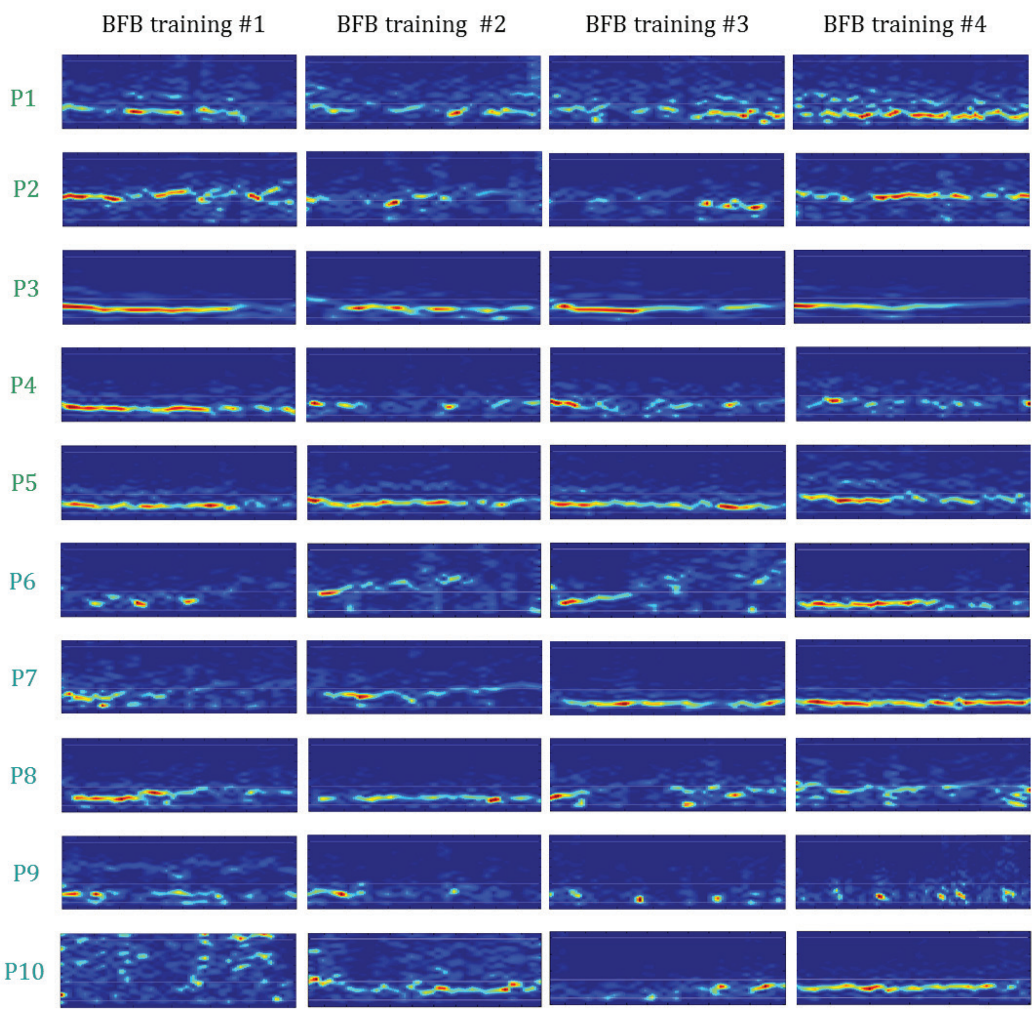


Fig 11.12 The time-frequency power spectrum plots for all participants in all biofeedback training trials.

groups of participants with different occupations. Both groups showed a similar learning curve. For most of the participants, their performance could be improved along with the training trials. As suggested by (Wulf et al. 2010), various factors may influence the learning curve, such as the task complexity, previous experience, focus on attention, motivation, and the number of practice.

For a traditional biofeedback training with the assistance of a therapist, the biofeedback protocol and instructions from the therapist can be the essential factors that influence the learning curve. In other casual biofeedback training program, like the biofeedback mind room in this study, there was few instructions and guidance from the therapist during the training. Hence, the usability of the interface, the understandability of the display, the explicitly of the biofeedback information, and the user experience with the interaction may play a stronger role in facilitating self-learning. This study did not investigate the effects of these factors on the learning process. However, the difference of the learning curves between the two groups reveals that the physical quality and the physiology of the participants can be another critical factor that affects the biofeedback-assisted learning.

In the biofeedback-assisted training, RESonance system assisted users to learn 'resonant breathing' skills for enhancing the HRV. The resonant breathing refers to a slow and smooth breathing pattern at a rate of about 4 to 7 breaths per minute (Lehrer et al. 2000). According to Ganong & William (1995), this resonant breathing rate is much slower than a typical breathing rate for a healthy adult at rest (12 to 18 bpm). For young soccer players, regular physical training increases their lung capacity and strengthens respiratory muscles, which make their breathing deeper and slower than the average people. Therefore, regulating the breathing rate to a slow frequency around six bpm seemed easier for them. The power spectrum plots revealed that the soccer players could perform well in the first training trial. They required little time to adjust their breathing to the resonant frequency which produces a spike of HRV at about 0.1 Hz. In contrast, the Ph.D. students' entry ability seemed lower than the players since their habitual breathing rate tend to be faster. They may need more time and practice to acquire the skills of breathing regulation. As shown in Fig 11.12, P6, P7, and P10 performed poorly at their first training trial. It took time for them to reach their peak performance at the last trial.

We think biofeedback-assisted self-regulation is similar to other learning processes, such as motor learning and language learning. Besides the external feedback, learning protocol, equipment, and instructions, the learning curve with biofeedback also depends on the 'level' of the learner himself. Here the 'level' refers primarily to the physical quality. A good physical quality may lower the barrier to entry and shorten the learning curve. Taking this study as an example, the players could easily regulate their breathing into a 'resonant frequency', while most Ph.D. students performed poorly at the first trial. We do not think that the good physical quality will lead to a success of skill acquisition. As shown by the learning curves in Fig 11.9 and 11.10, the students outperformed the players in the last training trial regarding the slow breathing and improved HRV. These findings are very interesting and enlightening for us.

Based on the participants' physical quality, we consider the students as novice or non-expert users while the players as experienced or expert users. Thus, how to lower the barrier to entry for the non-expert users, and how to continuously engage the expert users are two key issues for biofeedback-assisted self-learning. We suggest that a desirable biofeedback technique should have a low barrier to entry, a shallow learning curve, but also an active engagement of learners in long-term use. The solution might be not just about the biofeedback interface but more dependent on the innovation of the mechanisms and strategies for biofeedback learning.

For novice users, the learning goal tends to be far from their physiological baseline. It might require more effort to regulate their physiology to the targeted status. In the early phase of self-regulation, the bio-data is likely to be unstable or not ideal yet as a learning material for feedback. During this time, the direct feedback of bio-data tends to be of little help but to confuse or frustrate the users. On the other hand, for experienced or expert users, the learning goal seems very easy to achieve. It requires less effort to regulate their physiology to the targeted status. For them, the lack of change in feedback content and form tends to decrease the motivation and engagement of self-regulation, which might impede the development of skills. At the end of this chapter, we suggest 'adaptive biofeedback' for facilitating the self-learning with biofeedback. The research on adaptation of interface for biofeedback system is limited. To the best of our knowledge, the adaptive biofeedback system is an area that has not yet been studied extensively. The different learning curves lead to the need for a more 'smart' feedback mechanism, which can adapt the feedback source, information load, interface modality and the task difficulty in response to a user's physiological status, achieved performance, and practice time. We elaborate on the concept of adaptive biofeedback in the next chapter, section 12.4.2.

PART IV

In this last part of the thesis, we present general discussions of the findings and limitations. We formulate our answers to the research questions and conclude our contributions to the biofeedback research and design for stress management. We indicate four future research directions in biofeedback: Inherent Biofeedback, Adaptive Biofeedback, Casual Biofeedback and Peripheral Biofeedback.

12
Conclusions and Discussions

12.1 Answer to the Research Question 1

- How to design 'Natural Coupling' for biofeedback interaction that facilitate the user's understanding of physiological data?

12.1.1 Natural coupling in presentation mapping

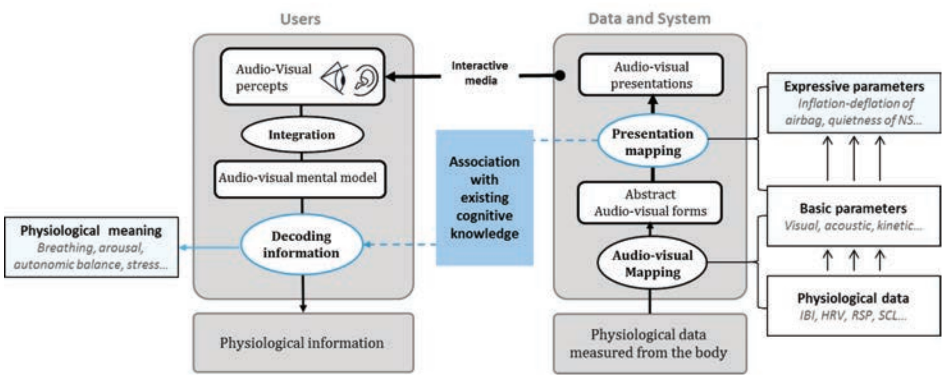


Fig 12.1 A natural coupling in the presentation mapping might facilitate user's understanding of the data meaning by enhancing the association between the biofeedback data and existing cognitive knowledge

As shown in Fig 12.1, the presentation mapping introduces a set of new parameters which are beyond the basic acoustic, visual, and kinetic parameters. These new parameters are related to how a user perceives or understands the interface expressions and therefore referred to as 'expressive parameters' (Rasmussen et al. 2012). We found that in most of existing biofeedback interfaces, the expressive parameters are usually used to improve aesthetics, enhance playfulness or address user experience so that the users can perceive and experience the biofeedback displays as beautiful, playful, or novel. However, few of biofeedback interfaces use the expressive parameters to define the interface's expressions for facilitating the user's understanding of physiological data. The biofeedback interfaces mediate the user's regulation and reflection on their physiology. We think this mediation should facilitate intuitive understanding and interaction with the biofeedback data. In this thesis, we used the idea of 'Natural Coupling' (Wensveen et al. 2004) in the presentation mapping design to facilitate the association between the interface's expressions and human bodily processes or a symbolic image of life. Following the idea of Natural Coupling, unifying the interface expressions and the represented physiological processes can make the self-regulation intuitive; associating the bio-data visualization with an image of life can make the biofeedback representations meaningful to everyday users.

12.1.2 Our explorations

As shown in Table 12.1, in our design explorations, we practiced the idea of 'Natural Coupling' in different interfaces. In the presentation mapping, we mainly focused on three aspects of Natural Coupling: dynamics, modality, and expression. The following explains these three aspects in our design cases.

Modality

Firstly, in our designs, the sensory modality of biofeedback displays was selected to be in harmony with the user's somatic experience of a self-regulated physiological process. Taking breathing regulation as an example, the human respiration is accompanied by airflow, breath sound, and the expansion/contraction of the chest cavity. When we take deep breathes; our breathing movement can be seen, heard and felt by our senses. In LivingSurface (S2), the wind-driven actuation of the surface was designed to 'mirror' the airflow of human breathing. The touch sense (tactile feedback) through the inflation/deflation of BwT enables users to feel the

Table 12.1 Natural coupling embodied in the design cases presented in this thesis

Design cases	Characteristics for natural coupling	Expressive parameters of the interface	Related or reflected Physiological processes or states
HeartBloom	Expression	Density of flower petals	Heart rate level
		Shape of the flower outline	Heart rate rhythm
StressTree	Expression	Growth pattern, branches density, leaves color	Heart rate variability
LivingSurface	Dynamics	Vibration (Surface #1)	Heartbeat
	Modality, Dynamics	The window's swaying with wind (Surface #2)	Breathing
	Dynamics, Expression ,	Curves and bulges outward (Surface #3)	Breathing
BwT	Modality, Dynamics	Inflation and deflation of an airbag	Breathing
BioSoundscape	Modality, Expression	Wind sound	Breathing
	Expression	Quietness of the nature soundscape	HRV
	Expression	Richness of the nature soundscape	Arousal level
DeLight	Expression	Brightness transfer between distributed lights	Breathing
	Expression	Green-blue colored light	Calm and relaxation results

breathing guidance intuitively along with breathing regulation. The up and down of the wind sound in BioSoundscape is also in harmony with the breath sound.

Dynamics

Secondly, the dynamics of interface display (time, position, speed, force) are coupled to the dynamics of the represented physiological processes (respiration rate, heartbeat activities, IBI oscillation). The discrete heartbeat activities are coupled to the discrete vibrations of LivingSurface (S1). A smooth breathing movement makes LivingSurface (S3) bulge and flatten continuously, smoothly and rhythmically.

Expression

Thirdly, the expressions of interface display reflect the physiological processes or indicate the physiological meaning. In the metaphorical visualizations, the static expressions are related to the semantics of the created visual images. The heart rate level is reflected by the size of flower. The flexibility of heart rhythm is reflected by the shape of flower. The stress level is reflected by the appearance of the StressTree. In the other interfaces that present the physiological processes, the aspect of expression is closely related to the dynamics. In DeLight, the breathing movement is reflected by the brightness transferring between a far and a near light. In BioSoundscape, the arousal level is reflected by its richness.

12.1.3 A reference design process

Here, we summarize our design processes as a reference process that is also the answer to research question 1. Firstly, we suggest understanding the physiological and health-related meaning of the biofeedback data. The fluctuations of IBI data indicate breathing movements during deep breathing, a reduced skin conductance level suggests lower arousal and higher calmness, a long-term reduced HRV indicates chronic stress, and a short-term improved HRV suggests a good result of breathing regulation. The biofeedback displays should not only give users the bio-data but also supply their meanings. Therefore, we argue that the design of biofeedback representation should start from understanding the data's meaning.

Secondly, designers could further clarify the characteristics of the biofeedback information, e.g., whether it indicates a discrete state or a continuous process, and whether the feedback is concurrent or terminal. If it is only terminal feedback showing a physiological state, e.g., a long-term stress level, the designers could strive for a semantic association between physiological states and interface expressions. If it is concurrent feedback to show a physiological process, e.g., real-time breathing and IBI data, the designers need to know the attributes of the data including the range, the update frequency, and the different changing patterns. The designers could address the dynamic expressions of the interface to simulate or mirror a specific physiological activity. Especially in the design of presentation mapping, the designers need to refine expressive parameters for natural coupling, such as the distribution of brightness or the quietness of nature soundscape. Then, in the audio-visual mapping, they can further decompose the expressive parameters into the basic parameters to couple with the data, such as kinetic parameters of actuators, acoustic parameters of a sound generator, and light parameters of the lighting controller.

12.2 Answer to the Research Question 2

- How to design ambient biofeedback for facilitating stress management?

In this thesis, we have explored the ambient biofeedback display by utilizing nature sounds and ambient lights. The initial intention is simple: we hope to put the biofeedback system into 'invisible background', where the users can perceive their internal physiological states from an environment without computer screens. An ambient biofeedback display allows the users to perform relaxation training in a more natural, comfortable and relaxing condition, such as sitting on a yoga mat, leaning back on the chair, or walking around the room. In the context of stress management, we have the following experiences in designing ambient biofeedback for both stress intervention and relaxation training.

12.2.1 Ambient biofeedback displays should blend into everyday settings

Firstly, we suggest an ambient biofeedback display should be aesthetically pleasing, decorative, and unobtrusive to everyday settings. In auditory modality, we used the nature sounds for ambient display. Nature sounds are often used as a natural augmentation to the indoor acoustic environment for its wholesome effects on relaxation. More importantly, nature sounds are among 'everyday sounds' around us, which makes them well suited for ambient display due to its naturalness, intuitiveness, and subtleness. For the visual modality, we used ambient lights because it is an integral part of everyday settings. Similar to the nature sounds, the colored lights (cool-tone) also have mood-enhancing and relaxation effects. In addition to lights and nature sounds, plenty of everyday objects in the physical environment can also be used or redesigned for ambient display through their subtle changes in form, movement, sound, color, smell, temperature, and light. The wallpaper of LivingSurface in this thesis and the shape-changing table from Feijs & Delbressine (2017) can be recent examples.

12.2.2 Ambient biofeedback displays should embrace Calm Technology

Biofeedback techniques inform us about our internal states and assist us in self-regulation by providing a fair amount of physiological information to us. To avoid causing an extra information burden, it is crucial for biofeedback design to embrace the principles of Calm Technology, which suggest making use of the periphery of our attention. For stress management, an ambient biofeedback system should have the potential for both peripheral stress intervention and centered relaxation training.

In chapter 7, we explored a nature soundscape model that aims to allow users to perceive biofeedback information without being overwhelmed. The nature soundscape model helps to mix, tune, modify various nature sounds in such a way that the resulting soundscape can be experienced as a harmonious sonic environment. For instance, BioSoundscape enables the listeners to perceive the information by holistically listening to the nature soundscape without giving attention to the details of sound. With the same goal, in the design of ambient lighting interface, we selected the saturation as the lighting parameter that links to the chronic stress level. The slow changes of saturation are subtle and unobtrusive. We envision BioSoundscape and DeLight to be an 'always-on' ambient display, which may lie in the periphery of users' attention. Their potential to inform the users about the stress level peripherally allows the stress intervention to be done in a user-friendly and calm way.

12.2.3 A distributed ambient displays for a sense of immersion

When a user perceives his increased stress level through a warmer ambient light or a more vibrant soundscape, the stress-related information moves from the periphery of attention to the center, and might further trigger him to cope with stress by using some self-regulation skills, such as deep breathing or arousal modulation. During this stress-coping process, the ambient displays are not to create ambient awareness but serve as an assistance to facilitate self-regulation and relaxation. For better engagement of self-regulation, an ambient display can be designed for creating a sense of immersion in our experiments. Here, the 'distribution' has two major implications: distribute the displays to different physical locations, and distribute the displays to different sensory modalities.

In RESonance (chapter 10), IBI and HRV data are presented by a set of ambient lights, and a nature soundscape consisted of various sounds. The ambient lights are distributed to different distances to the user. The distribution enables brightness to transfer between the near and far lights to create a 'self-centered' experience. In the nature soundscape, the wind sound is rhythmically distributed to the left and right channels. The bird sounds are modulated with different echo and reverb effects to create a sense of distance. The distributed displays center around the user may create a sense of immersion. On the other hand, the same information is distributed to both auditory and visual modalities concurrently, multi-sensory stimuli could also work together enhancing the immersive experience.

12.3 Limitations

This work has limitations. As indicated by the framework in Fig 12.2, our work focuses on the stage of biofeedback representation, but the other elements including bio-sensing technologies, physiological computing, and evaluations of the system in everyday use have not yet been investigated. These challenges for biofeedback still require future studies to address.

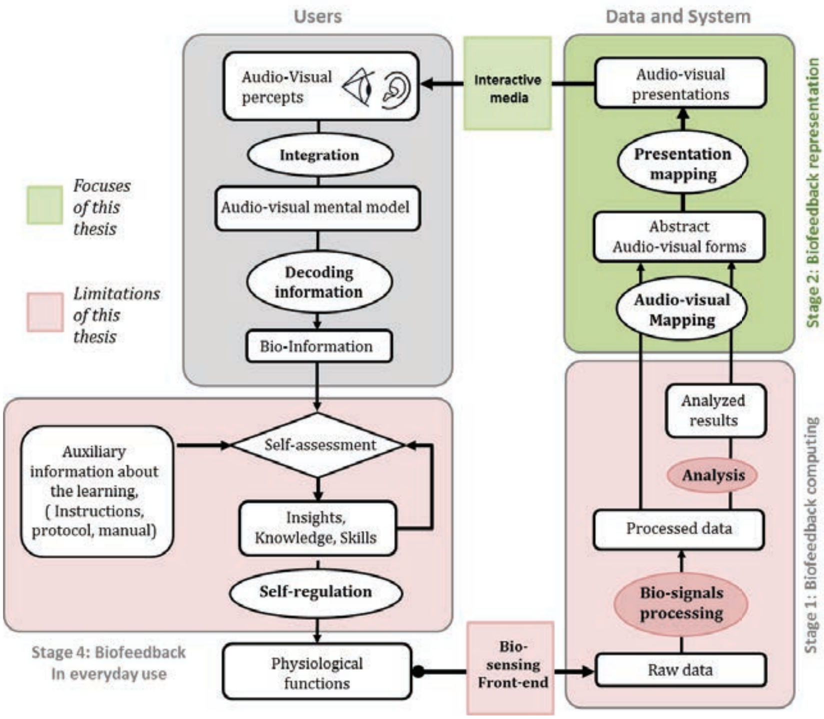


Fig 12.2 The focuses and the limitations of this thesis

First of all, new bio-sensing technologies were not explored. To ensure the accuracy of measurement, we used the professional bio-sensors in the standard ways. In our experiments, a photoplethysmogram (PPG) sensor was fixed on the fingertip with a clip to measure the blood volume pulse for calculating IBI and HRV. The respiration data was measured by a strap sensor attached to the chest or abdomen position. In the lab experiments, these bio-sensing approaches can be acceptable, but for everyday use, new bio-sensing techniques are required. In addition to the accuracy, stability and robustness, the unobtrusiveness and wearability (contact type) of the bio-sensing need to be addressed.

Secondly, a higher-level physiological data processing was not explored. The approaches of data processing used in this work were relatively simple and basic. For HRV biofeedback, the LF/HF ratio can be calculated by frequency domain analysis (Al Osman et al. 2016). For multimodal biofeedback, the multiple types of physiological data can be analyzed in combination to obtain more indicators of self-regulation result, such as the cardiac-coherence score calculated from the respiratory trace and IBI wave (Meier & Welch 2016). Moreover, more stress-related and emotional information can be obtained through affective computing (Healey & Picard 2005; Arroyo-Palacios & Slater 2016).

Thirdly, the prototypes in this work were only tested in lab-based or exhibition-based evaluations, which might not be adequate to reveal their advantages and disadvantages in real everyday use. These assessments focused on the usability, user experience and effectiveness of new biofeedback systems in relaxation training, while the desirability of biofeedback interface was not evaluated. It could have been investigated how people interact with the biofeedback systems and integrate the biofeedback-assisted relaxation training into their daily routine. More insights could have been obtained from long-term field studies in everyday settings.

12.4 Future Directions for Biofeedback Design

The design explorations in this thesis show our efforts in pushing the biofeedback techniques into people's everyday life. New biofeedback representations were designed by addressing the 'natural coupling' in presentation mappings. New ambient biofeedback interfaces were created with lights and nature sounds. Although some promising findings and design implications were presented, this work might still be a probe into the potential of biofeedback in stress management. More future explorations are needed from the HCI. Here we indicate four directions for future research.

12.4.1 Inherent Biofeedback

As suggested by Wensveen et al. (2004), the feedback from an interactive system can be distinguished into three types: functional feedback, augmented feedback and inherent feedback. This thesis mainly focuses on augmented biofeedback design. The advances in HCI constantly enrich the augmented biofeedback. On the one hand, the augmented audio-visual displays amplify the subtle physiological changes so that the user can perceive easily. On the other hand, we think the augmented feedback may drown out the inherent feedback from the body. According to Shusterman (1997), the inherent bodily feedback is also referred to as somatic sensation. Höök et al. (2016) proposed a strong concept named 'Somaesthetic Appreciation Design' which suggests the biofeedback interaction should subtly support users' attention inwards, towards their own body.

The works in this thesis inspire us and motivate us to question ourselves whether the biofeedback can be designed as an inherent feedback, not to drown out somatic sensations with fancy external displays, but to enhance our sensitivity to own somatics. We envision the 'Inherent Biofeedback' becoming a tangible artifact which can be worn or attached on the body or placed very close to the body, like an extension of the body. It senses our internal states and delivers the biofeedback through somatic sensations (e.g., touch sense). As such, the biofeedback can be perceived inherently through the sensory experience of the contact with the interface on or close to the body. One recent instance might be a wearable HRV biofeedback device named '*Lief* smart patch[1]', which can be directly attached to skin and provide feedback through subtle vibration.

1. Lief biofeedback smart patch: https://www.getlief.com/, retrieved:13-11-2017.

12.4.2 Adaptive Biofeedback

In chapter 11, we have demonstrated that the acquisition of self-regulation skills may take time and require practice. Based on different physical qualities and physiological conditions, different users may show a unique learning curve with biofeedback. For some users, it may need a longer time to familiarize with the biofeedback representations. For others, it may take more practice to internalize self-regulation skills. Here, we asked ourselves: how a biofeedback system could adapt itself to optimize the biofeedback learning curve for each user. This might be the first motive for 'Adaptive Biofeedback'. According to Schneider-Hufschmidt et al. (1993), Adaptive User Interfaces (AUIs) are interfaces that can adapt to a specific user, provide feedback about the user's knowledge and predict the user's future behavior, such as goals, preferences, and actions. For a self-training/learning system, Wulf (2007) found that adaptive feedback shows advantages in the adaptation to the learner's needs, in the promotion of more in-depth information processing, and in the involvement of the learner in the learning process, resulting in increased motivation and learning effect. To date, the research on the AUIs for biofeedback system is limited.

For future research, we propose the concept of 'Adaptive Biofeedback' with three adaption abilities (Yu 2016). Firstly, an adaptive biofeedback interface should support information display in multiple sensory modalities. The sensory modality of feedback can be personalized and adapted to the context of use. For instance, the biofeedback can be presented in a tactile modality for privacy in a public office and switched to a multimodal display with sound and lights for immersion in a home environment. Secondly, the biofeedback information source and dense should adapt to the user performance and the results of the biofeedback training. At the beginning of training, instead of a user's own bio-data, the system can display a pre-set bio-feedforward guidance signal (e.g., 0.1Hz breathing guidance) to get the user familiar with the system and get the bio-data ready for feedback. When the user's bio-data become clear and stable, the guidance signal can be reduced, and meanwhile, the bio-data can be enhanced and presented as the biofeedback. When the user achieves the goal in the current training, the biofeedback data can be gradually weakened, and an accompaniment relaxation-induced signal (e.g., relaxing background music) can be increased. Thirdly, to further motivate and engage the user in training, the system could also allow users to self-control the training 'flow'. After achieving the goal, they may choose to relive the current training task or upgrade to the next-level task with increased difficulty.

12.4.3 Casual Biofeedback

In chapter 2, we have found that most of the biofeedback applications for stress management are based on a pre-scheduled training program. Typically, a long-term training program may consist of multiple sessions, each of which may take 10 to 30 minutes. These studies demonstrate that a regular training routine seemed to be essential in the acquisition of skills. However, we think using biofeedback in such a way also limits its broader use in people's everyday life. Beyond a tight program-based biofeedback training, we believe the very potential of biofeedback can be reached with a loose and casual use. Here we suggest the third direction — 'Casual Biofeedback'.

On the one hand, we think a stressful situation in real life offers the best timing to learn how to manage stress. On the other hand, the 'busy-ness' of today's life fragments people's time. It becomes difficult and even stressful for people to stick to a preset training routine. The fragmentation of time should lead to fragmentation of biofeedback training. No need to have a pre-planned program, the biofeedback system can be used immediately in a real stressful scenario or casually in small moments of time. We believe the casual biofeedback-assisted mediation, self-reflection, and self-training can provide maximum benefit in everyday stress management. We envision future biofeedback techniques can be integrated into the everyday objects that are 'within easy reach', e.g., a pen on the desk or a gadget in the pocket. The user can always use it to 'check' their stress level and manage the stresses at any time when he/she feel stressed or get a spare minute.

12.4.4 Peripheral Biofeedback

In addition to regular biofeedback training and casual biofeedback practices, improving self-awareness about stress is also essential in stress prevention and intervention. Biofeedback techniques can not only assist self-regulation but also inform users about their stress level and initiate them to cope with stress. In fast-paced everyday work, people's attention is almost fully occupied with work tasks. We do not want biofeedback displays to become too 'loud', occupying the center of attention and causing a sense of burden or pressure. Therefore, we propose a future direction of 'Peripheral Biofeedback'. In line with the vision of Calm Technology (Mark Weiser & John Seely Brown 1997), we believe that leveraging human attention abilities in peripheral interactions (Bakker et al. 2015) will support biofeedback-assisted self-reflection to better work for stress management in today's busy lifestyle. With advancements in IoT technology, we envision that an increasing number of everyday objects can act as the interactive media supporting peripheral biofeedback interactions in daily life.

12.5 Summary of Contributions

The contributions of this thesis take different forms. Besides the implications for biofeedback design described in the previous sections 12.1 and 12.2, the contributions of this work also include a biofeedback interaction framework, a systematic review, a series of design cases and deliverables. Some prototypes have been further developed and contributed to different fields. The RESonance Mind Room has been used by Philips Sports Vereniging (PSV) football sports club as the biofeedback training system for helping the soccer players in relaxation training. The HeartBloom has been used by Hartstichting (Dutch Heart Foundation) as a mobile fundraiser for charitable fundraising (see Appendix E). We summarize the contributions of this thesis as follow:

In Part I:

1. A biofeedback interaction framework has been proposed to describe the information pipeline and the human-computer interaction in biofeedback systems (chapter 1).
2. A systematic review has been conducted to summarize the last 25 years of research on biofeedback techniques for stress management regarding bio-sensing technique, data processing, feedback presentation, usage scenarios, and evaluation approaches (chapter 2).

In Part II:

3. A set of HRV sonifications have been developed as an audio alternative to the visual tachogram (chapter 3).
4. Two metaphorical visualizations that embody a 'natural image' have been developed to present IBI and HRV (chapter 4).
5. Four life-like shape-changing interfaces that embody a 'living object' have been designed to present IBI and HRV (chapter 5).
6. A tangible interface that simulates 'human breathing movement' has been developed to provide tactile breathing guidance (chapter 6).

In Part III:

7. A nature soundscape modal has been developed for supporting both calm information display and a calming experience. (chapter 7).
8. An auditory interface has been developed with nature sounds for ambient biofeedback display (chapter 8).
9. A lighting interface has been developed for ambient biofeedback display (chapter 9).
10. An audio-visual interface has been developed by integrating nature soundscape and ambient lights for immersive relaxation training (chapter 10).
11. The effectiveness of biofeedback in facilitating the learning of self-regulation has been investigated in a long-term biofeedback training program (chapter 11).

12.6 Concluding remarks

We started this thesis with the question: how to bring biofeedback techniques closer to everyday use so that average people can harness it intuitively with comfort. In this thesis, we sought our answers in the field of HCI. We have developed six new biofeedback interfaces in different modalities. These works addressed the presentation mapping by following the concept of Natural Coupling. Specifically, we mapped biofeedback data to the 'expressive parameters' of the interfaces, in which way the interface expressions can be inherently linked to or naturally associated with physiological processes (e.g., heartbeat, breathing), states (e.g., high arousal, stress level) or meanings (e.g., healthy or unhealthy). The results indicate that the Natural Coupling embodied in biofeedback representations could facilitate the users' understanding of the physiological meaning related to their bodily process, stress and health state.

In this thesis, we have also explored ambient biofeedback by using spatial lights and nature sounds. Although light is an integral part of everyday settings and nature sounds are among 'everyday sounds' around us; however, we found they have seldom been used for biofeedback display. The results of the user studies show that the ambient biofeedback with spatial light (DeLight) and nature sounds (BioSoundscape) can not only efficiently convey the biofeedback information assisting users in breathing regulation but also enhance the relaxation effects reducing the users' arousal level. The combination of both (RESonance) can further enhance immersion, improving the users' engagement with biofeedback training and facilitating a state of mindfulness.

The work in the thesis is mostly exploratory. When we look back and examine the whole research process, we found in most of our work; design becomes a resource for new knowledge through the empirical effects it produces. We designed new biofeedback interfaces with various HCI technologies to address emerging challenges in biofeedback. The user studies with these designs provided the insights into what the users would do and feel when the newly designed interfaces were being used. The results and insights were generalized into a reference design process and some design guidelines that can be utilized by other researchers and designers to propose new ideas and produce better biofeedback designs. We hope our work could be a starting point for initiating a new field of 'Everyday Biofeedback'.

APPENDICES

A

Name:____________ Date:________________

State-Trait-Anxiety-Inventory (STAI-S, State subscale)

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you feel right now, that is, at this moment. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

	Not at all	Somewhat	Moderately so	Very much so
1. I feel calm	1	2	3	4
2. I feel secure	1	2	3	4
3. I am tense	1	2	3	4
4. I feel strained	1	2	3	4
5. I feel at ease	1	2	3	4
6. I feel upset	1	2	3	4
7. I am presently worrying over possible misfortunes	1	2	3	4
8. I feel satisfied	1	2	3	4
9. I feel frightened	1	2	3	4
10. I feel comfortable	1	2	3	4
11. I feel self-confident	1	2	3	4
12. I feel nervous	1	2	3	4
13. I am jittery	1	2	3	4
14. I feel indecisive	1	2	3	4
15. I am relaxed	1	2	3	4
16. I feel content	1	2	3	4
17. I am worried	1	2	3	4
18. I feel confused	1	2	3	4
19. I feel steady	1	2	3	4
20. I feel pleasant	1	2	3	4

B

Name:____________ Date:________________

Relaxation Rate Scale

Please rate your relaxation state at this moment.

Not Relaxed	1	2	3	4	5	6	7	8	9	*Totally Relaxed*

C

Questionnaires for evaluation of Heart Rhyme Audio-forms

Name:______________ Date:__________________

This survey is used to evaluate the new biofeedback displays. Please circle only one number for each of six items that follow.

1. This form of display is difficult to understand.

Strongly Disagree	1	2	3	4	5	*Strongly Agree*

2. The form of feedback is difficult to follow.

Strongly Disagree	1	2	3	4	5	*Strongly Agree*

3. I often felt lost in the control of the feedback.

Strongly Disagree	1	2	3	4	5	*Strongly Agree*

4. The feedback display made me stressful.

Strongly Disagree	1	2	3	4	5	*Strongly Agree*

5. The feedback display made me tired.

Strongly Disagree	1	2	3	4	5	*Strongly Agree*

6. The feedback display made me sleepy.

Strongly Disagree	1	2	3	4	5	*Strongly Agree*

D

UnWind: A Musical Interface of Biofeedback for Relaxation Training

1 Introduction

In chapter 7, a model of nature soundscape (NS) has been developed through an empirical study. In chapter 8, we applied this NS model to the design of BioSoundscape, an auditory biofeedback interface which modulates nature sounds responding to the user's physiological data. In this appendix, we move forward in designing a musical biofeedback system by combining the nature sounds with sedative music. Unwind consists of a BioSoundscape layer and an additional music layer. The BioSoundscape layer still functions as the auditory biofeedback display to facilitate users' self-regulation. The combination with music aims to further foster a relaxing experience by leveraging the power of sedative music.

In everyday life, music is a source of pleasure for many of us. Music can be an excellent medium to help people cope with stress through its facility to regulate emotion and boost mood (Knobloch & Zillmann 2002). Numerous studies show that music listening may influence the heart activity (Iwanaga et al. 2005), blood pressure (Knight & Rickard 2001; Chafin et al. 2004), breath (Bernardi et al. 2009) and physiological arousal (Rickard 2004). A fast and dynamic musical piece may have an excitative effect while a melodious and slow one has a sedative effect. Pelletier (2004) suggests that listening to relaxing music helps the listener calm down and moderate arousal. Labbé et al. (2007) and Iwanaga et al. (1996) indicate that sedative music can reduce psychological anxiety and physiological stress. The anxiolytic and therapeutic effects of music have been widely studied and documented in stress management and music therapy (see, e.g., Mandel [1996]). Calming, relaxing and sedative music are also frequently used in relaxation exercises as a background accompaniment (see, e.g., Robb [2000]).

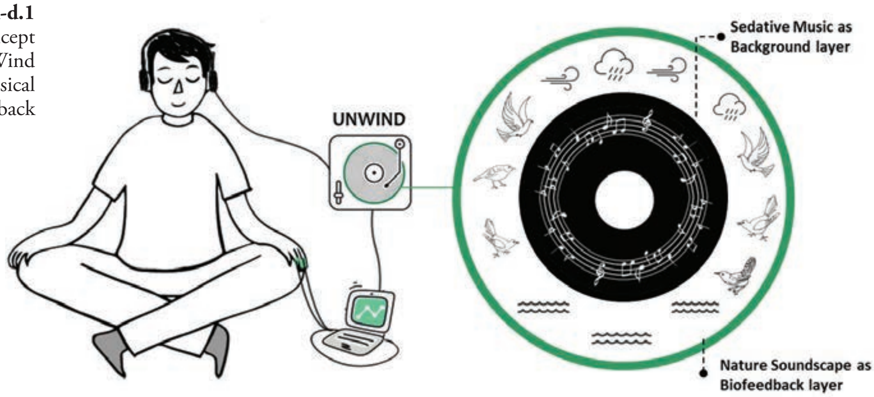
The literature review in chapter 2 shows that in the context of stress management, most of the single-modal auditory biofeedback interfaces take the musical form. Musical biofeedback interfaces can be divided into two categories. The first is realized by modulating the musical parameters with the bio-data. For instance, Yokoyama et al. (2002) proposed a musical biofeedback system which presents heart rate data by adjusting the pitch and tempo of a melody. Bergstrom et al. (2014) presented the physiological data by controlling musical tempo and volume. In the second category, the interfaces modify sound effects of existing music for biofeedback display. For instance, Bhandari et al. (2015) developed a musical biofeedback system by adding white noise to a musical piece according to the user's respiration pattern. Similarly, Harris et al. (2014) developed a biofeedback system that encourages slow breathing by adjusting the quality of a music recording in proportion to the user's respiration rate.

As described in chapter 3, in our early explorations on auditory biofeedback, we have also tried to present biofeedback data in the form of music. We developed four auditory displays by mapping the timing variations of heartbeats to the musical rhythms to represent HRV data. The results of the user study were less positive than expected. Some participants reported that the audio displays were changing too quickly to perceive the pattern of changes; this made them confused and even anxious. The repeated musical structure led to a feeling of tiredness. The unfamiliarity with the musical output also increased the psychological burden to the users. In other musical biofeedback systems mentioned above, the audio outputs are also quite different from those musical pieces that are arranged by a composer. It is still a challenging task to present information by modulating the musical structure. Real-time music notation techniques (also referred to as dynamic musical scores) emerge in recent years (Freeman & Colella 2010). These techniques may offer a better way to get into the essence of music and create a more melodious musical interface controlled by physiological data. As the real-time notation is a relatively new field, few tools exist for non-composers. Moreover, how to fascinate the aesthetic of a musical form might be another big challenge for designers with little music knowledge and skills.

New-age music is a genre of music intended to promote artistic inspiration, relaxation, and optimism (Smith & Joyce 2004). It may create a peaceful atmosphere for reading, yoga, meditation, and relaxation. Nature sounds are a common integrant in new-age music. For instance, Dean Evenson combined his peaceful flute music with the sounds of nature in 1979. Another example could be the album by Matthew Lien "*Headwaters - Music of the Peel River Watershed*" in which instruments and the sounds of the watershed were composed and assembled into a piece of music. Goel & Etwaroo (2006) found that listening to birdsong accompanied by music could reduce the self-reported negative effect. Now for us, the explorations on BioSoundscape and the inspirations from New-age music point to a new direction for designing a musical biofeedback interface without the need to deal with the musical structure.

In this appendix, we further develop the auditory biofeedback into a musical form. Unwind was designed to facilitate breathing training and foster a relaxing experience through music listening. The originality of UnWind lies in presenting the physiological information through a nature soundscape that is integrated with sedative music as a new form of musical biofeedback. The combination sounds like a piece of New-age music. In the experiment, we examine the possible effects arising from this combination, and investigate the effectiveness of UnWind in a relaxation training, towards optimizing the breathing pattern, enhancing the heart rate variability and moderating the arousal level and reducing the subjective stress and anxiety.

Fig appx-d.1 The concept of UnWind musical biofeedback



2 Design of UnWind

UnWind is designed for an HRV biofeedback system, which provides the IBI and HRV data for assisting breathing regulation in a relaxation training. The bio-sensing and data processing have been described in the previous chapters, e.g., section 5.3.2. The structure of UnWind musical interface is shown in Fig appx-d.2. It is composed of two layers: BioSoundscape layer and music layer. The BioSoundscape serves as the 'biofeedback informative layer,' while the sedative music serves as the 'background layer'.

The music layer contains a collection of sedative music, which is widely used in music therapy. Sedative music mainly refers to those pieces of melodic, soothing and comforting music with few major changes in pitch, dynamics or rhythm. Sedative music features by a slow tempo that may be similar to that of the resting heart rate from 60 to 80 beats per minute (bpm) with a soft dynamic range (Iwanaga & Moroki 1999). Some studies showed that heart rate and blood pressure were decreased by sedative music (Knight & Rickard 2001). A wide variation of music has been selected as the samples of sedative music for the experiment in the previous studies. A collection of new age music, classical piano, slow modern jazz, and American Indian flute music have been selected in (Voss et al. 2004). As documented in (Lingham & Theorell 2009), the sedative collection was selected from a broader range: baroque string music, Greek vocal music, relaxing Tibetan music, relaxing jungle music, lullaby music, Pink Floyd ('*Wish you were here*') and Dolly Parton ('*I will always love you*'). Some classical music is melodious, delicate, soft, and beautiful. They are also regarded as sedative music and used in music therapy, such as Erik Satie's *Gymnopedie No.1* (Iwanaga et al. 1996) and Beethoven's *Moonlight Sonata* (Lorch et al. 1994). Following Iwanaga et al. (1996), we selected the original piano version of Erik Satie's *Gymnopedie No.1-No.3* and *Gymnopedie No.1-No.3* for the music layer of UnWind.

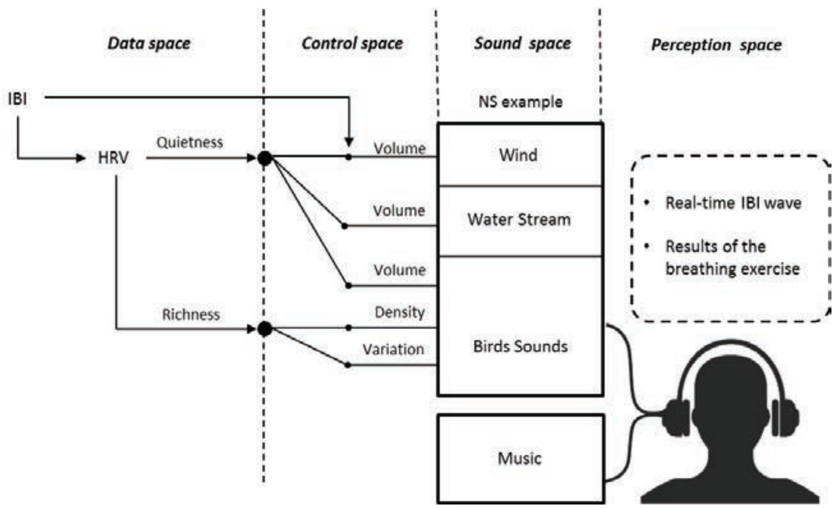


Fig appx-d.2 Structure and presentation mapping in UnWind interface

The design and implementation of the BioSoundscape layer have been described in chapter 8, section 8.2. The presentation mapping is similar to the previous design but adapted to present IBI and HRV data, as shown in Fig appx-d.2. The IBI data is presented by the wind sound, and HRV data is presented by the perceptual 'quietness' and 'richness' of the soundscape. The IBI data is mapped to the increment and decrement on the basic wind volume (± 20%). The HRV_{16} (0-225ms) is negatively coupled with the volume of wind and water, and the volume, density, and variations of the bird sounds. Firstly, the volume of the selected audio contents was normalized to the same modest value with the sound editing software. The HRV_{16} is mapped to the amplification factor of the volume of all sounds from 0 to 0.1. The HRV_{16} is mapped to the playing frequency of bird sound from 30 sounds/min to 10 sounds/min. Each time the bird sound is being played, the HRV_{16} determines the range of the sample selection (25 to 5 samples). As such, when the HRV_{16} value increases with deep breathing, the volume, density, and variation of the sounds will be reduced. According to the NS model described in chapter 7, the nature soundscape can be perceived to be a quiet and simple environment.

3 Evaluation

3.1 Participants

Forty college students (22 females, 18 males, age range: 20–30 years) participated in the study through informed consent procedures. Each participant was compensated with 5 euro for their participation. The participants did not practice yoga, meditation or deep breathing exercise regularly. Furthermore, the participant did not have any experience with biofeedback.

3.2 Experiment design

The experiment was aimed to investigate the feasibility of UnWind as a musical interface for biofeedback display and examine the possible effects arising from the combination of BioSoundscape and sedative music. We evaluated Unwind in a 2×2 factorial experiment with sedative music and biofeedback as independent factors; each factor has two levels: presence or absence; see Table appx-d.1. The participants were randomly assigned to one of four conditions: listening to pre-recorded nature sounds (NS), listening to pre-recorded nature sounds with music (NM), with audio biofeedback through BioSoundscape only (NSBFB), and with musical biofeedback through the combination of BioSoundscape and music (NMBFB).

Table appx-d.1 The 2×2 factorial experiment design

Factor level	Non-Biofeedback	Biofeedback
No music	NS (Pre-recorded nature sounds)	NSBFB (Biofeedback-controlled nature sounds)
With music	NM (Pre-recorded nature sounds with sedative music)	NMBFB (Biofeedback-controlled nature sounds with sedative music)

In all conditions, the participants perform a 10-minute relaxation training after a 10-minute mentally challenging task. In all conditions, the participants were suggested to relax with deep breathing in the relaxation training. In non-biofeedback conditions (NS, NM), the participants were exposed to a piece of pre-recorded nature sounds with or without music layer; the nature sounds were controlled by the program to shape a quiet and simple NS with a repetitive wind movement of a random cycle from 6 to 10 seconds. In biofeedback conditions (NSBFB, NMBFB), the nature soundscape was controlled by the participants' real-time IBI and HRV data. The participants were told that the wind sound would increase and decrease with their breathing and when they perform well in the breathing regulation, the soundscape will become quiet and simple.

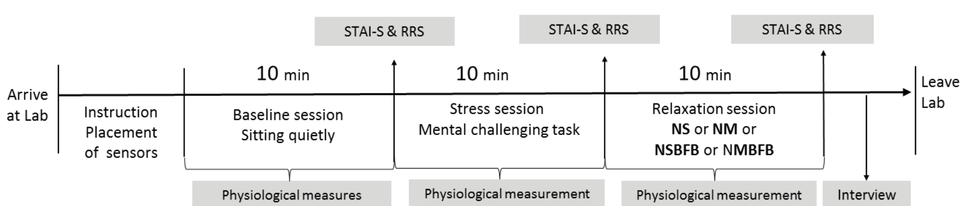
3.3 Measurements

Psychological and physiological measures in the evaluation are the same as the experiment for BioSoundscapce in chapter 8. The stress/anxiety level was measured by Relaxation Rating Scale (RRS) and State-Trait-Anxiety Inventory-State subscale (STAI-S). Physiological measurements included heart rate, respiration rate, heart rate variability indices (SDNN, LF%), skin conductance responses. For details, refer to the section 8.4.3. A follow-up interview was conducted at the end of the experiment. The interviews were loosely structured with a focus on three questions: "*What did you like about the experience? What did you not like about the experience? Any other comments?*" There was enough space for the participants to freely feedback on their experience. The interview data is used to support the interpretation of the quantitative data and provide indications of psychological states.

3.4 Procedure

The experiment followed a procedure as shown in Fig appx-d.3. The participants were assigned to one of the four conditions by a computer-generated list of random numbers. The experiment consisted of a baseline session, stress session, and a relaxation session. During the baseline session, the participant sat quietly on the chair. During the stress session, the participant completed a mentally challenging task (10 minute in total) which consists of a Stroop color-word test and a Mirror-tracing test. Only when the participant finished the Stroop color-word test, he/she could start the second mirror tracing test. During the relaxation session, the participants performed relaxation training with/without biofeedback assistance. After each session, the participant completed the STAI-S and the RRS surveys. Finally, the follow-up interview was conducted. All participants were tested individually in a small testing room furnished with a recliner chair, rug, lamps, and biofeedback equipment. In all conditions, the participants wore an acoustic noise-canceling headphone (*Bose, QuietComfort 25*) to block the noise in the environment and listen to the music.

Fig appx-d.3 Procedure of the experiment



		NS		NM		NS-BFB		NM-BFB	
		Stress	Relaxation	Stress	Relaxation	Stress	Relaxation	Stress	Relaxation
HR	*Mean*	74.88	71.76	77.69	73.19	74.11	70.45	73.88	68.39
	Std.D	11.71	14.91	5.77	7.76	10.08	11.71	10.74	9.37
	Std.E	3.70	4.72	1.82	2.45	3.19	3.72	3.39	2.96
	Sig.	0.057		**0.007**		0.120		**0.000**	
SCRs	*Mean*	7.04	3.78	6.67	3.19	7.50	3.99	5.36	1.58
	Std.D	3.34	1.87	3.05	2.03	3.52	2.99	2.20	1.38
	Std.E	1.05	0.59	0.96	0.64	1.11	0.94	0.69	0.44
	Sig.	**0.002**		**0.000**		**0.000**		**0.001**	
HRV-SDNN	*Mean*	73.21	92.40	62.59	78.25	68.41	108.66	50.92	70.41
	Std.D	24.81	55.25	17.29	31.27	26.18	30.32	10.19	12.78
	Std.E	7.85	17.47	5.47	9.89	8.28	9.58	3.22	4.04
	Sig.	0.198		0.067		**0.002**		**0.005**	
HRV-LF%	*Mean*	58.81	58.89	60.39	53.47	65.38	74.72	54.32	81.13
	Std.D	10.50	18.67	14.11	20.63	10.39	20.69	20.28	10.69
	Std.E	3.32	5.90	4.46	6.52	3.28	6.54	6.41	3.38
	Sig.	0.988		0.247		0.134		**0.011**	
RSP (cycle /minute)	*Mean*	20.16	17.05	20.43	14.41	21.44	7.28	21.27	8.98
	Std.D	2.36	4.3	2.97	4.55	5.43	2.49	5.76	3.91
	Std.E	0.75	1.47	0.94	1.44	1.72	0.79	1.82	1.24
	Sig	**0.021**		**0.002**		**0.000**		**0.000**	
RRS (score)	*Mean*	4.10	6.20	4.7	7.7	3.4	7.0	4.20	7.50
	Std.D	1.79	1.81	1.89	1.05	1.65	1.05	1.39	1.50
	Std.E	0.57	0.57	0.59	0.34	0.52	0.33	0.44	0.47
	Sig	**0.014**		**0.000**		**0.000**		**0.000**	
STAI (score)	*Mean*	43.10	36.50	39.70	28.90	46.20	35.40	49.9	32.5
	Std.D	7.92	7.18	7.62	5.63	9.73	7.73	11.05	10.67
	Std.E	2.51	2.27	2.40	1.78	3.07	2.45	3.49	3.37
	Sig	0.009		**0.001**		**0.000**		**0.001**	

Table appx-d.2 The results of the measures in four conditions

4 Results

Within each condition, we compared the measures between the stress session and relaxation session by using dependent t-test. The results are shown in Table appx-d.2. Then we calculated the percent changes of the measures in relaxation session (relative to their levels during the stress session) for each condition. A two-way ANOVA (General Linear Model/ univariate analysis in SPSS) was conducted to test the effect of the sedative music and biofeedback on the relaxation.

4.1 Physiological measures

Heart rate (HR). As shown in Table appx-d.2, heart rate for the participants in all conditions decreased during the relaxation session, and the decrease of the HR was significant in two music conditions (NM, NMBFB), which suggests that the sedative music has the potential to reduce the cardiac responses to the stressful condition. Fig appx-d.4 shows the percent decrease in HR during the relaxation session (relative to their levels during the stress session) for each of the four conditions.

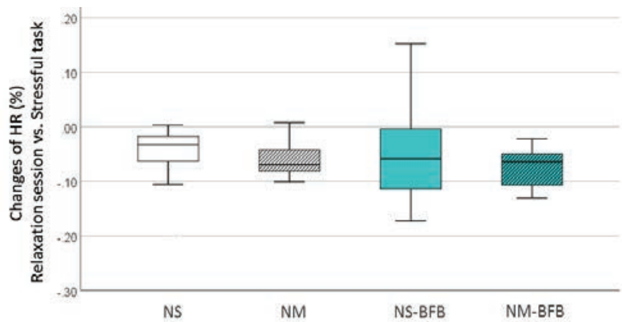


Fig appx-d.4 Simple Boxplot of the percent changes of the HR in four conditions

Skin conductance responses (SCRs). As shown in Table appx-d.2, the participants in the four conditions (but particularly those with sedative music) showed a significant reduction in SCRs in the relaxation session. Fig appx-d.5 shows the percentage of reduction in SCRs during the relaxation session relative to its level during the stress session. The participants in the music conditions showed a large decrease than the non-music conditions (NS, –44.2±20.2% *vs*. NM, –51.3±25.9%; NSBFB, –50.8±20% *vs*. NMBFB, –56.9±28.4%). This result suggests that the relaxation session with the combination of sedative music and nature sounds may be more effective than listening to nature sounds only at lowering arousal.

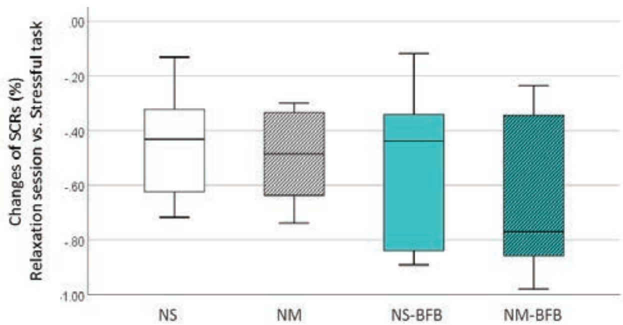


Fig appx-d.5 Simple Boxplot of the percent changes of the SCRs in four conditions

Respiration rate (RSP-R). Table appx-d.2 shows that the participants showed a significant reduction in RSP-R during relaxation session of all conditions (relative to its level during the stress session). In the biofeedback conditions (NSBFB, NMBFB), the participants' RSP-R dropped significantly below ten bpm during the relaxation session. While in the non-biofeedback conditions, the decrease in RSP-R was relatively small. Two-way ANOVA shows a main effect of biofeedback on respiration rate during the relaxation (F=41.926, p<0.05). This result suggests that the biofeedback conditions were effective in encouraging slow breathing during the relaxation session.

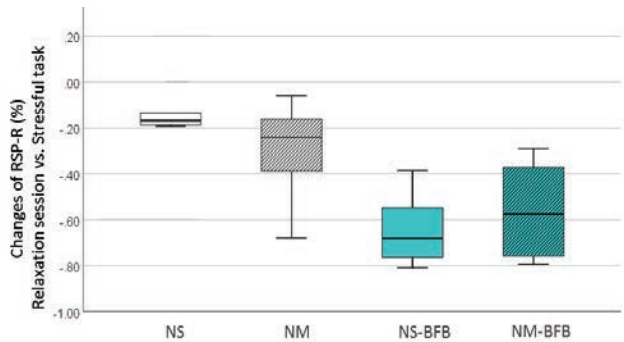


Fig appx-d.6 Simple Boxplot of the percent changes in the respiration rate in four conditions

Heart rate variability (SDNN). The Standard Deviation of IBI data (SDNN) is calculated as the HRV index in the time domain. Fig appx-d.7 shows the percent decrease in SDNN (relative to its level during the stress session). The participants in the four conditions (but particularly in biofeedback conditions) showed a significant increase in SDNN during the relaxation session. Two-way ANOVA shows a main effect of biofeedback on HRV during the relaxation (F=5.624, p<0.05), which suggests that the biofeedback was effective in enhancing the heart rate variability during the relaxation exercise.

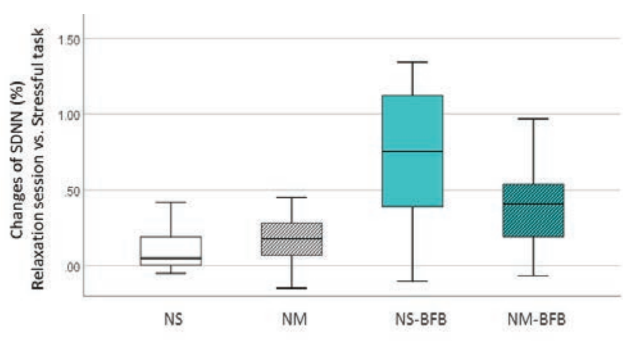


Fig appx-d.7 Simple Boxplot of the percent changes of the SDNN in four conditions

Heart Rate Variability (LF%). We used LF/(LF+HF), also named as LF%, as the HRV index in the frequency domain. Fig appx-d.8 shows the percent changes of LF% (relative to its level during the stress session). The participants in the non-biofeedback conditions showed a small decrease during relaxation session (NS, −0.6±33.6% *vs.* NM, −26±44%), but a large increase in biofeedback conditions (NSBFB, +5.8±28.2% *vs.* NMBFB, +30.7±30.7%). Two-way ANOVA shows a main effect of biofeedback on HRV during the relaxation (F=8.0, p<0.05), which suggests that the biofeedback conditions were effective in enhancing the power of the low frequency of heart rate variability data during the relaxation exercise.

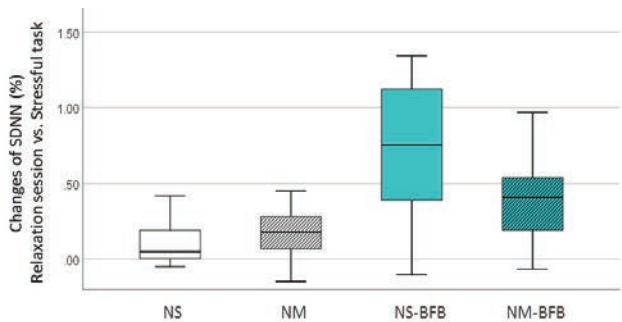


Fig appx-d.8 Simple Boxplot of the percent changes of LF% in four conditions

4.2 Psychological self-report

Relaxation rating scale (RRS). The participants reported their subjective relaxation experience with a 9-point Likert relaxation rating scale (1: not relaxed at all; 9: most relaxed). Table appx-d.2 shows the self-report RRS in the relaxation sessions was significantly higher than the stress sessions. As shown in Fig appx-d.9, the participants in the two music conditions (NM, 3.0±1.56; NMBFB, 3.3±1.64) reported a more significant increase in RRS than in the non-music conditions (NS, 2.10±2.18; NSBFB, 2.9±0.74).

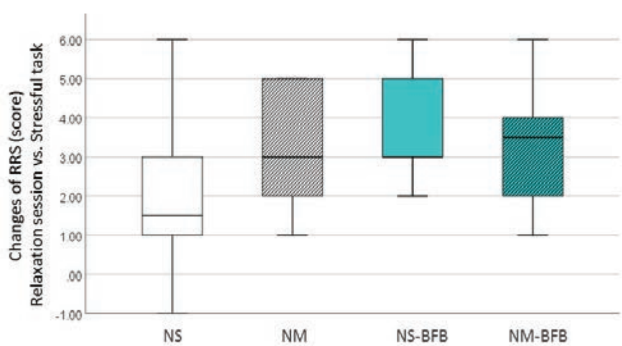


Fig appx-d.9 Simple Boxplot of the score changes of RRS in four conditions

State-Trait-Anxiety-Inventory (STAI). The participants reported a decreased STAI score after the relaxation session in all conditions (NS, −6.6±6.4; NM, −10.8±6.5; NSBFB, −10.8± 3.4; NMBFB, −17.4±11.6). Fig appx-d.10 shows the changes of STAI scores (relative to their levels during the stress session) for four conditions. A two-way ANOVA shows a main effect of both factors: music (F=5.1, p<0.05) and biofeedback (F=5.1, p<0.05) factors in self-report anxiety level. This result suggests that music biofeedback is more effective at reducing the subjective anxiety after the stress than music-listening or auditory feedback alone.

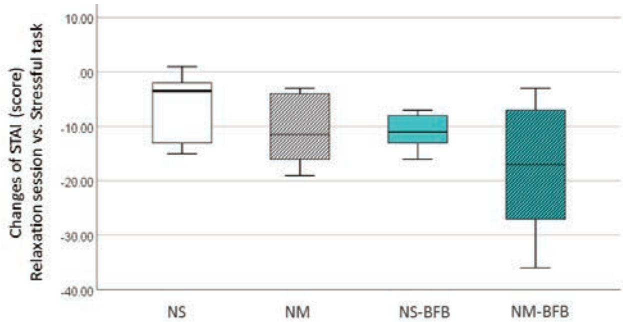


Fig appx-d.10 Simple Boxplot of the score changes of STAI in four conditions

4.3 Interview data

NS Condition. The responses indicate that listening to pre-recorded nature sounds made the participants relaxed. Most participants stated that nature sounds brought them with some natural pictures in mind. Four participants expressed that these images led to a pleasant experience and an enhanced relaxation. The nature soundscape also created some imagery feel, such as some feelings described in the interview "*It made me feel as if I was in a forest*" and "*I felt myself sitting by the river and watching the birds sing around the trees*." The participant's preferences on the specific nature sounds might greatly influence the relaxation experience. For instance, one participant stated that "*the sound of the water stream and birdsong are very relaxing, give me a feeling of peace.*" However, two participants thought the birdsong of Silvereye was annoying, and another one participant thought the birdsong of owl was disturbing. Also, some participants suggested giving the users more options for the selection of nature sounds or ambience sounds, such as the sound of the sea or the coffee shop ambience.

NM Condition. The responses indicate that listening to the combination of sedative music and the nature sounds was calming and soothing for most of the participants. Most participants stated that the slow rhythm of the music (Erik Satie's *Gymnopedie No.1*) made them calm down and relax quickly. Three participants thought the music could create an atmosphere and set the mood which was mentioned in the interview as "*pleasant*", "*beautiful*", and "*happy*". However, two participants thought the frequent birdsong damaged the quiet atmosphere created by the sedative music. They suggested us to reduce the frequency and the types of birdsongs. A few of participants hope to select the music which they felt relaxing for them. A wider collection of music was suggested, such as the Anasazi flute, classical guitar, and more new piano music (e.g., Yiruma's *River Flows in You*).

NSBFB Condition. The merits of the NSBFB condition are similar to the NS condition as described above. The responses also indicate that the biofeedback through changing wind sound made the participants focus on their breathing and more conscious of their heart rate rhythm. Six participants stated that the sense of controlling the wind sound with the breathing regulation was relaxing. Three participants mentioned that when the nature soundscape was becoming increasingly quiet along with the deep breathing, they felt a sense of accomplishment, which made them more relaxed. In contrast, two participants said that they felt more stressed when the changes of the nature sounds were less than expected or very different from their expectation. Another disadvantage was that the repeated nature sounds made some participants feel fatigue and boring after a few minutes exercise.

NMBFB Condition. Similar to the NM condition, most participants reported that the combination of sedative music and nature sounds was relaxing and calming. Four participants thought the outcome music is very suitable for yoga and meditation. Three participants noticed the relationship between the nature sounds and the music. They said when they attempted to breathe slowly and deeply, the nature soundscape became quiet and the music seemed to come to the 'foreground'. And when they stopped deep breathing practice, the nature sounds became loud and came to the 'foreground' while the music was hard to hear. This motivated them to continue with the deep breathing. In contrast, three participants reported they were attracted quickly by the music so that they did not pay much attention to the changes of the nature sounds. This weakened the effects of biofeedback. Two participants thought the nature sounds (particularly the wind sound) reduced the quality of the music. Compared to the NSBFB condition, there was no participant reported the feeling of fatigue and boredom in the relaxation training. Same with other conditions, the participants also suggested a personalized selection and combination of the natures sounds and the sedative music.

5 Discussion

In this appendix, we have presented a musical biofeedback interface which presents IBI and HRV data by combining the nature sounds and sedative music as a new form of New-age music. UnWind allows the users to perceive their physiological information by listening to music for relaxation training. We compared the UnWind musical biofeedback against the NS-based auditory biofeedback, music listening and nature sounds listening, with five physiological measures and two psychological measures as dependent variables. Our results demonstrate that UnWind musical interface (NMBFB) is comparable to the NS-based auditory biofeedback display (NSBFB) for assisting the relaxation training, regarding the improvement of the respiration pattern and heart rate variability. When compared to the two non-biofeedback conditions, biofeedback leads to a lower respiration rate (RSP) and enhanced heart rate variability (SDNN and LF%). We found that employing the combination of sedative music with nature soundscape is more effective in modulating arousal than being exposed to nature sounds only. When compared to the two non-music conditions, the sedative music leads to lower arousal levels (SCRs and HR). The results from subjective ratings also indicate that musical biofeedback leads to a larger reduction of anxiety level (STAI).

In general, a musical interface can be either based on the parameter-mapping sonification where the bio-data is directly mapped to the musical parameters such as musical tempo, pitch, and volume (Bergstrom et al. 2014; Yokoyama et al. 2002), or harnessing the characteristics of human musical perception, such as the quality of music and the perception on the soundscape (Bhandari et al. 2015; Harris et al. 2014). In a biofeedback-assisted relaxation training, how to create a continuously musically pleasant experience is an important design issue, which may be a challenge and may also require some degree of knowledge about music and composition. Therefore, in recent years, the advanced sonification approaches, such as model-based methods, and the real-time algorithmic composition tools have been investigated increasingly. In this appendix, we proposed a new approach to design a musical display, which does not deal with the complex musical structure and composition, but can still harness the effect of sedative music for relaxation experience. Compared to the above-mentioned parameter-mapping sonifications or the modulations of music quality for biofeedback, we saw some strengths of UnWind biofeedback interface.

Firstly, we do not need to manipulate the parameters and the structure of music to present information. Instead, we add a layer of nature sounds as the integrant of the music for information display. The two-layered structure of musical interface reduces the difficulty in the design of music expression and allows designers to take advantage of the existing well-composed sedative music. Because the output of the interface largely depends on the selected music, the listening experience is more predictable. Secondly, the two-layered musical interface makes it possible to update the selection of the nature sounds and the music for different users and the applications. Thirdly, besides the informative functions, nature sounds itself create the sensation of experiencing a natural acoustic environment or an imaginary nature scene, which may also foster calmness. Last but not least, as biofeedback encourages the learning of self-regulation, the biofeedback techniques and relaxation training are likely to cause a certain degree of anxiety for some new users. In these cases, the sedative music could lower the anxiety caused by the biofeedback techniques. As shown in our results, the participants in NM and NMBFB conditions reported a higher level of relaxation (RRS) and a lower level of anxiety (STAI) respectively.

On the other hand, we think there are still some issues in UnWind need to be future investigated. Although there is no interaction between the nature sounds layer and the music layer; their intersection may still affect the user perception and experience on the audio output. For instance, the disharmony or mismatch between nature soundscape and the selected music might reduce the listening experience. The music layer might interfere with the user's perception of the information presented by the nature sounds, which reduces the effectiveness of biofeedback. As shown in our results, the NSBFB condition is relatively more effective than the NMBFB condition in facilitating slow breathing, which suggests that the BioSoundscape might be more effective in presenting information without the presence of the music. From our experience with this study, we have realized the importance of the balance between the functional and the experiential aspects of the interface when designing a biofeedback display for managing stress. To achieve this, we suggest an adaptive musical interface where the 'proportion' of BioSoundscape, i.e., the 'apparent degree' of information layer, can be adjusted based on the user's performance and physiological states. When the users need the feedback information for supporting self-regulation, the information layer should be more noticeable and perceptible. On the contrary, when the users have mastered the self-regulation skills and achieved the optimal training results, the link between the nature sounds and the data source could be weakened, and the information layer could even fade out.

6 Conclusion

We view the outcome of this study as an encouraging indication that the combination of nature soundscape and sedative music may be used as a new type musical biofeedback for stress management and relaxation training. We have established that musical biofeedback is both effective in short-term use for relaxation training and good at reducing the physiological arousal and the psychological anxiety. The responses from the interview also imply that the musical feedback can reduce the fatigue and boredom due to the variation in musical expressions.

E

BioPlotter: An Interactive Installation for Physical Biofeedback displays

1 Introduction

In chapter 5 and 6, we have reported our attempt in the shape-changing biofeedback interfaces with the idea of 'natural coupling'. LivingSurface actuates the physical surfaces behave anthropomorphically, dynamically representing the user's internal state. Some expressive qualities of the physical transformation, e.g., life-like movements, are used to facilitate user perception and understanding of their own bodily data. Breathe with Touch allows the users to feel digital breathing guidance directly. Beyond the information display, BwT harnesses the natural human ability to perceive the information through the touch sense. In the area of biofeedback, the concepts of tangible user interface (Ishii 2008) and shape-changing interfaces (Rasmussen et al. 2012) has also been practiced by other researchers, especially in the form of 'interactive installation' and with an emphasis on the user engagement and experience. For instance, *Metaphone* (Šimbelis et al. 2014) is a biofeedback installation that reflects the participant's physiological data through the machine movements. *Mind Pool* (Long & Vines 2013) provides real-time feedback of the participant's brain activity via the fluctuations on a pool of magnetically reactive liquid. These works revealed one advantage of physical displays—they are good at engaging users in interacting with the work for experiencing it.

With digital fabrication technologies, the production of physical visualizations (Jansen et al. 2013) becomes more accessible to the researchers and designers in HCI. Compared to traditional digital visualizations which map data to pixels,

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This chapter is largely based on

Yu, B., Arents, R., Funk, M., Hu, J. and Feijs, L.M., 2016, May. HeartPlotter: visualizing bio-data by drawing on paper. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 1794-1799). ACM.

Yu, B., Arents, R., Hu, J., Funk, M. and Feijs, L., 2016, February. Heart Calligraphy: an Abstract Portrait Inside the Body. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (pp. 675-680). ACM.

physical visualizations use specifically physical forms to represent data. Many researchers have explored the representations of personal data through physical visualizations. For instance, Khot & Mueller (2013) designed a system called *SweatAtoms* that transforms the heart rate data into 3D printed material artifacts. M.-H. Lee et al. (2015) visualize the users' accumulated activity logs by engraving patina-like patterns on the wristband of activity trackers. Stusak et al. (2014) present the design of *Activity Sculptures*, visualizing the running activity data in various physical objects created by 3D printers, such as necklace, a lamp, and a jar. These studies suggest that the physical visualizations of personal data can strengthen emotional connections with the data and affect the user's long-term behaviors by fostering comparison, reflection, and social communication.

In this appendix, we present the design of BioPlotter, an interactive biofeedback drawing machine. BioPlotter serves as a new physical biofeedback display that visualizes the physiological data into a drawing with the mechanical movements of a pen plotter. As emphasized by Ishii (2008), physical displays show a potential to enhance the way in which people interact with the digital information, leading to enhanced engagement and user experience. With BioPlotter, we intend to explore whether the physical displays through a pen plotter and its paintings may improve the user engagement in a biofeedback training. In the following, we present the design process of BioPlotter, including the system framework, bio-sensing techniques, preliminary exploration on plotter control, and the visualization design. Then we present the evaluation of BioPlotter for the biofeedback training and discuss the results regarding the training effects and the user experience. Next, we present two disseminations from the lab-based BioPlotter to broader fields, namely Bio-Art creation and public charitable fundraising.

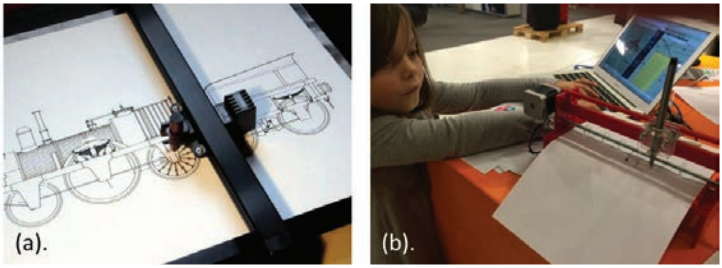
2 The Prototype BioPlotter

2.1. Pen Plotter

A pen plotter is a type of output devices used in the past for printing vector graphics. A plotter gives a hard copy of the output by drawing on papers with a pen, see Fig appx-e.1(a). Currently, pen plotters have been replaced with wide-format inkjet printers. Plotters typically work together with a computer-aided design (CAD) software. A plotter receives a graphical vector file in the HPGL format (Hewlett-Packard Graphics Language [1]) and translates its statements into a series of movements of the pen. Importantly, pen plotters can be actuated with separate commands from a serial port, performing separate movement such as 'pen-up', 'pen-down', or 'move from point A to point B'. As such, a pen plotter can be controlled manually to draw dots and lines with specified speed and pressure. A pen plotter can work as an interactive drawing machine, responding to the user's

1. Hewlett-Packard Graphics Language: http://www.sxlist.com/techref/language/hpgl/commands.htm, retrieved:13-11-2017 inputs in real time, see Fig appx-e.1(b).

Fig appx-e.1
The system framework of BioPlotter (a) pen plotter was used as the standard hard-copy output device for computer graphics (b) new interactive pen plotter



Recently, pen plotters have been re-discovered as an interactive device by many designers and artists. For instance, Oliver & Niall (2015) developed an electro-mechanical sound device based on a *Roland-DXY* pen plotter. Michel (2015) designed a plotter-based interactive installation, which draws abstract graphics taking the input of the audience's facial expression. Besides working with commercial plotters, many researchers have also developed their prototypes of interactive drawing machines, which are similar in action to the pen plotters. For instance, *AtmoSPHERE* (Du et al. 2015) visualizes the movements in its surrounding space by the traces of the ball movements on a sandbox table. Except for these interactive installations, few studies have explored the feasibility of the pen plotter as a physical display of information. For us, its working process is very attractive, not because of its capability to print digital graphics in high quality but also its step-by-step drawing process. Therefore, we think there is still great, untapped potential of pen plotters for physical information display.

2.2 Designing the interactive mode of pen plotter

The working mode of pen plotters is 'one command, one movement.' Because a simple visual element like a line might take more than three physical movements to complete (i.e., pen-down, move from point 'A' to 'B', and pen-up). The direct mapping from the data to the parameters of plotter control has a limited capacity of visualization and tends to be confusing for the data representation. Therefore, in the design of the plotter-based physical display, we propose the concepts of *Action* and *Move*, the former interfaces to the data and the latter deals with the plotter control commands, as shown in Table appx-e.1. BioPlotter uses an 'action-based' working mode to present data. *Action* can be regarded as the basic unit of the plotter's machine expression and the 'bit' in physical visualization. When coupling with the data, the frequency of *Action* can be associated with data sample rate. For instance, one action can be triggered at the fixed sampling rate of 0.5Hz (i.e., breathing signal) or by the heartbeat with changing intervals. *Move* refers to one mechanical movement executed with one drawing function. One *Action* may consist of several *Moves*. BioPlotter uses a series of repetitive actions to represent the data with physical movements and compose physical visualizations.

Table appx-e.1 Data, Action, Move, Drawing functions and Plotter commands

DIGITAL	*PHYSICAL MOVEMENTS*	*DRAWING FUNCTIONS*	*PLOTTER COMMANDS*
Data →	Action → Move 1 ↓ Move 2 ↓ Move 3 ...	• *Pen Up ()* • *Pen Down ()* • *Moving ()*	• *PU()* • *PD()* • *Velocity Select: VS()* • *Pressure Select: PS()* • *Plot Relative: PR()* • *Plot Absolute: PA()*

We package the HPGL-formatted plotter control commands into three basic drawing functions: *PenUp*, *PenDown*, and *Moving*. The *PenUp* and *PenDown* functions have no arguments; they simply send the plot commands (PU, PD) to switch the vertical positions of the pen: hanging over the paper or falling on the paper. The *Moving* function takes five arguments as the input, generating a package of commands for a single movement. Table appx-e.2 shows the details of each argument. The first argument specifies the mode of coordinate: relative movement (Rm) and absolute movement (Am). The second and third arguments work in pair handling the position of one movement. In Rm mode, they represent the angle (direction) and the magnitude. In Am mode, the second and third arguments represent the absolute X and Y coordinates. In Am mode, the pen can be easily moved to an arbitrary position within the range of the coordinate system of the plotter. Thus it is suitable for setting the pen to a specific position, such as the central point of radiation pattern or the starting point of the next row. In contrast, Rm mode is more suitable for constructing a specific shape with several lines of different length and angle. In both modes, the last two arguments are same, modulating the speed and pressure of the pen on the paper.

Table appx-e.2 Details about the arguments of the *Moving* function

Arguments	**Types**	**Descriptions**
Mode	Integer	Determines the working mode of one move **1:** Absolute move **2:** Relative move
X-coordinate/ Direction	Integer	In mode 1: determine the X value of absolute coordinate In mode 2: determine the angle value of relative movement
Y-coordinate/ Magnitude	Integer	In mode 1: determine the Y value of absolute coordinate In mode 2: determine the magnitude of relative movement
Speed	Integer	Determines the speed of one move
Pressure	Integer	Determines the pressure of the pen touching the paper

2.3 Exploring the expressiveness of pen plotters

Through the drawing function of *PenUp*, *PenDown*, and *Moving*, the data is packaged into the plotter commands to execute the physical displays. Before making BioPlotter completely functional for displaying multiple physiological data, we first explored the interactivity and effectiveness of the pen plotter with five basic mappings from the data to pen-down time, direction, magnitude, speed, and pressure. We aimed to clarify the questions that to what extent the users could perceive the information through the pen movements and the resulting physical drawings. We experimented with each mapping by using the real-time heart rate data as the input. Then we summed up the visual features of the drawings and the characteristics of the pen movements regarding interaction and experience. Here, we present the experimental drawings and the findings we concluded and used in the design of BioPlotter. The more details about the study can be found in our publication (Yu, Arents, et al. 2016).

- Pen-down time: through the functions of *Pen UP* and *Pen Down*, the sound rhythm of pen-up and pen-down could present the timing information of data. Pen-down time (the pen touching the paper) also influences the size and darkness of the drawn dots; the longer time the pen touching the paper, the ink would spread into a larger dot on the paper. The ability of dots in visual representation is limited. Fig appx-e.2(a) shows the drawing created by mapping the heart rate data to the pen-down time.
- The position of the move: by controlling the second and third arguments of the *Moving* function, the distance and the direction of the pen movement can be mapped to the data, creating a combination of lines of different lengths and angles. The maximum distance of a single move is limited by the speed of the move and the data update frequency. Fig appx-e.2(b) shows the drawings created by mapping the heart rate data to the distance of the move.
- The speed of the move: by controlling the fourth argument of the *Moving* function, the speed of pen movement influences physical drawing on thickness and texture (Fig appx-e.2-c). However, more importantly, it influences the mechanical sound whose pitch can correspond to the speed almost linearly. The faster the pen moves, the higher pitch sound the machine will generate. When the speed is coupled with the data, the machine sound could give the listener immediate audio feedback about data value.
- The pressure of move: by controlling the last argument of the Moving function, the pressure modulation is recognizable on the physical drawings because it mainly affects the friction between the pen tip and the paper, which results in different size, weight of the dots or lines, see Fig. appx-e.2(d).

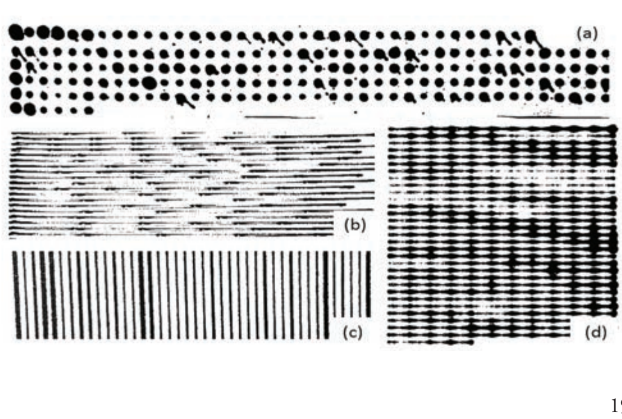


Fig appx-e.2
The experimental paintings created by mapping the heart rate data to (a) pen-down time mapping (b) the distance of the move (c) the speed of the move (d) the pressure of the move

2.4 System framework of BioPlotter

The framework of BioPlotter is shown in Fig appx-e.3. The Blood Volume Pulse (BVP), Galvanic Skin Response (GSR) and Respiration (RSP) signals are measured by a PPG sensor, GSR sensor and an RSP belt sensor with a *MindMedia NeXus-10* amplifier. The biofeedback program is developed based on the *Processing* platform. The program receives the BVP, GSR and RSP signals from the amplifier and processes the raw bio-signals into biofeedback data which is further translated into plotter-readable commands. Through a serial (RS-232C) port, these commands are transmitted to the pen plotter in real time, controlling the pen acting on the surface of the paper. The plotter used in our design is a small, desktop-sized flatbed plotter (a *Roland DXY-1100* from 1985). The pen moves back and forth on a travelling arm across the plotting table, plotting a graph on a piece of paper that is fixed over the rectangular flatbed table.

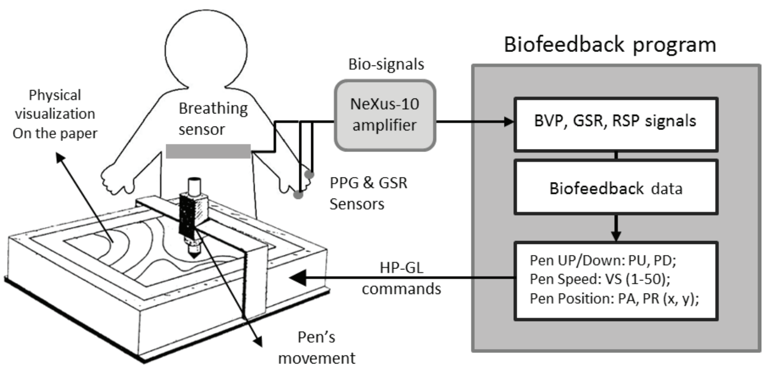


Fig appx-e. 3 The system framework of BioPlotter

2.5 Visualization design

The physical paintings of BioPlotter reply on the pen movements and the frictions between pen and paper. Here, we focus more on the former. The pattern of the pen movements is defined by the actions which are coupled with the data, see Table appx-e.1. Here we used the visualization design of HeartBloom described in chapter 4. BioPlotter translates the biofeedback data into the actions of the plotter; the pen then draws the 'flower' painting on the paper. Compared to the digital HeartBloom, the physical HeartBloom paintings are created with the following changes. Firstly, the physical 'flower' paintings were created by various types of physiological data, SCL, IBI and RSP signal. Secondly, BioPlotter offers more kinetic parameters to couple with the data, such as the pen position, speed, and pressure. Therefore, the physical visualization is mediated by the pen movements, which are realized by mapping data to the kinetic parameters, as shown in Table appx-e.3. We elaborate on the presentation mappings in the following section.

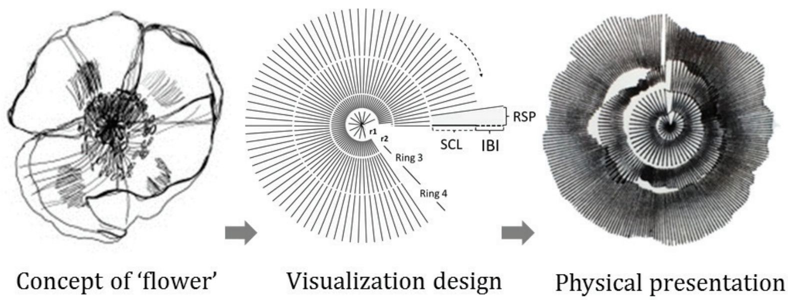


Fig appx-e.4 From the concept to digital visualization, to flower-shape physical paintings

2.6 Mapping design

To make the interaction explicit, BioPlotter implements a heartbeat-triggered interactive mode. Each heartbeat triggers one pen movement to draw a line. BioPlotter takes multiple types of physiological data as the input, including the heart rate (HR), inter-beat interval (IBI), respiration (RSP) and skin conductance level (SCL) data. The calculated physiological data are then mapped to the kinetic parameters modulating the pen movements, such as distance, direction, and the speed. The effect of the kinetic parameters can be further reflected on the physical paintings. The mapping between the biofeedback data to the kinetic and visual parameters are shown in Table appx-e.3.

Table appx-e.3 The mapping between the bio-data to kinetic and visual parameters

Data Space *Human physiology*	**Interaction Space** *Pen movement*	**Visualization Space** *Painting output*
Skin conductance level (SCL) Inter-beat Intervals (IBI)	Distance of each move	Length of the petals in one ring
Heart rate (HR)	Speed of each move	Thickness of each petal
Respiration trace (RSP)	Direction of each move	Rotation angle of each petal

Firstly, skin conductance level (SCL) data, as the index of the physiological arousal, control the 'size' of the flower painting. The flower's size aims to reflect the user's arousal level. When an individual is in a stressful state (with a high arousal level), the visualization will look like a 'withered flower bud.' In contrast, when an individual in a calm and relaxed state, the reduced arousal level will lead to a large flower and all 'petals' tend to launch outwardly. To achieve this, the basic radius of each ring is determined by the average value of SCL data measured in the drawing of the last ring. Secondly, the heart rate variability brings the fluctuations on the shape of the flower pattern. The IBI data modulate the increment on the basic length of each line (the radius of the ring), which decides the distance of each movement together with the SCL data.

Thirdly, the user's respiration influences the density of the lines in each ring. The respiration signal is resampled on the detection of the heartbeat and mapped to the rotation angle of the pen movements. When the user breathes in, the decreased respiration signal reduces the rotation angle of the next line and vice versa. Thus, a regular deep breathing will generate apparent changes of density distribution. When the rotation angle reaches the 360 degrees, the pen will move to the next ring. Lastly, the average heart rate is reflected by the overall density of the lines. Because the pen moves based on the heartbeat, the amount of lines in each ring is not fixed but dependent on the heart rate. Also, the speed of the movement is modulated by the heart rate data. A fast heart rate does not only lead to a fast rhythm of successive pen movements but also a fast speed of a single move.

3 The Evaluation of BioPlotter for Physical Biofeedback Display

3.1 Study design

We conducted a user study to evaluate BioPlotter as a physical display for biofeedback. The research question is whether the physical display from the BioPlotter would improve user engagement in a biofeedback-assisted breathing training. The experiment follows a within-subjects design with counterbalancing to avoid carry-over effects. Each participant completed two biofeedback sessions: one with the on-screen digital display and the other one with BioPlotter. In the digital biofeedback session, the participant sat in front of a computer and learned to control their physiological data with the 'flower' visualization on the screen. In the BioPlotter session, the participant received the biofeedback from the working of the plotter. The BioPlotter was placed on a tilted stand as shown in Fig appx-e.5.

Fig appx-e.5
Biofeedback breathing training with digital visualization on screen (left) and with BioPlotter (right)

We collected the HRV data (i.e., SDNN) and the self-reports on the user experience by using the User Experience Questionnaire (UEQ) (Laugwitz et al. 2008). The participants' subjective opinions were also collected in the interview at the end of the experiment. The interviews lasted about 5-8 minutes, during which the participants reflected on aspects of their experience with the on-screen display and the physical display of the BioPlotter and responded to the following questions:

Table appx-e.4 The question list in the interview

	Questions in the interviews
Q1	How would you describe your experience with on-screen display or BioPlotter?
Q2	To what extent did the feedback help you to be more aware of your heart rate and breath?
Q3	To what extent did you feel that you were able to influence aspects of your breath and heart rate?
Q4	What did you appreciate and dislike about the on-screen display or BioPlotter?
Q5	Do you have any other suggestions for how this work might be developed in the future?

3.2 Participants

We recruited 20 participants to take part in the experiment (ten females and ten males, aged between 24 and 35). Individuals that had any health problems associated with the cardiovascular system or that take drugs that affected cardiovascular functioning were excluded from the study. All participants gave the written informed consent and provided the permission for publication of photographs with a scientific and educational purpose.

3.3 Procedure

On arrival at the laboratory, the participant was fitted with the bio-sensors and relaxed quietly on a chair for 5 minutes. The physiological data collected in this period is used to normalize the participant's average HR, SCL, HRV, and respiration rate in the resting state. Then, a brief introduction was given to the participant: "*the purpose of the biofeedback session is to lower the arousal level and improve the heart rate variability by breathing regulation.*" The participant was randomly assigned to one of two groups, in which the order of the digital and physical biofeedback sessions is reversed, as shown in Fig appx-e.6. The biofeedback sessions were carried out without the experimenter present. At the end of each session, the participants completed the UEQ questionnaire and were asked to recall their experiences about biofeedback interactions in the interview.

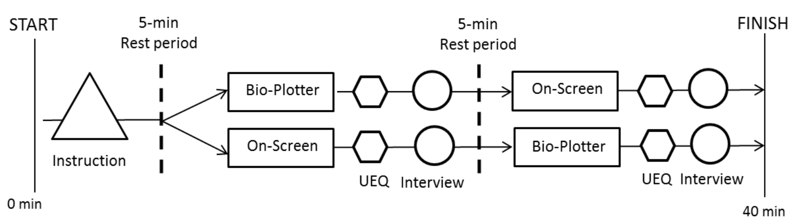


Fig appx-e.6 The procedure of the experiment

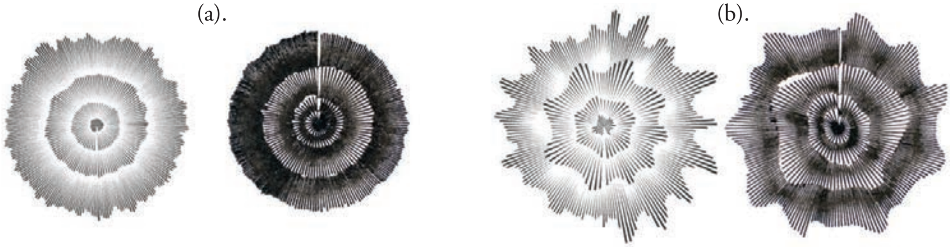
In both biofeedback sessions, the participants received the similar instructions: "*The presented 'flower-shape' graphics/ painting will reflect your physiology. The density of the 'flower petals' reflects your heart rate level. The higher your heart rate is, the 'petals' will be denser. The size of the 'flower' reflects your arousal level. The calmer and relaxed you are; a bigger flower you will create. The shape of the 'flower' reflects your heart rate rhythm. The texture of the 'flower' reflects the breathing pattern. When you breathe slowly and deeply, the output graphics/painting will show regular fluctuations on the shape and the distribution of density. Try to make a blooming flower with rich variations by regulating your breath more slowly and smoothly.*"

3.4 Created digital and physical visualizations

Fig appx-e.7 shows two groups of visualizations created by the participants with different performance on breathing regulation. Fig appx-e.7(a) shows the visualizations created by the participants who failed in breathing regulation. The density of the lines in the drawing is high due to a relatively high heart rate. Because the participant did not attempt the regulation of his breathing, the density and the shape of both on-screen and physical visualizations change very little. Fig appx-e.7(b) shows the visualizations created by the participant who has performed well in the breathing regulation with biofeedback information. The deepened and regular breathing movements lead to regular changes in the density of the lines. The enhanced HRV is reflected by the noticeable fluctuations on the 'flower' shape. These results suggest that the physical 'flower-shape' visualizations are effective in presenting the biofeedback information, including heart rate (lines density), respiration (density distribution), heart rate variability (fluctuations on the shape), and arousal level (size of shape).

Fig appx-e.7 The visualizations created (a) under normal breathing state (b) under slow breathing

(a). (b).



On-screen display | BioPlotter painting | On-screen display | BioPlotter painting

3.5 Quantitative results

Fig appx-e.8 shows the percent changes in SDNN (as the HRV index) for two biofeedback sessions compared to the pre-test period. The SDNN is improved significantly in both biofeedback sessions. There is no significant difference between the conditions comparatively. The HRV is associated with the breathing regulation. This result suggests that the biofeedback through both on-screen and BioPlotter displays can facilitate the participants' deep breathing which improves the HRV level. The SDNN data in the BioPlotter session shows a larger deviation, which was caused by a diversity of the participants' interactive behaviors with BioPlotter. We found the participants were more active in breathing training with the physical display. Their behavioral performance of breathing regulation seemed more diverse and exploratory. For instance, one participant reported that he speeded up or held his breaths intentionally to test the responses of BioPlotter.

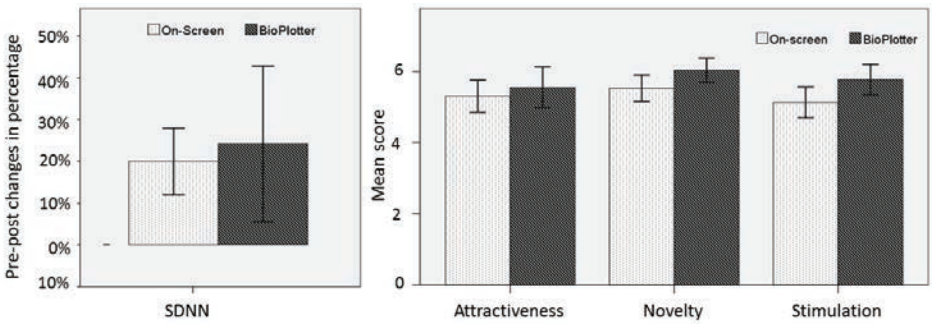


Fig appx-e.8 The results of HRV and UEQ questionnaires

The findings from UEQ questionnaires show that the hedonic quality aspect (Stimulation and Novelty) and Attractiveness of both interfaces are good. The mean score and the standard deviations of the UEQ for on-screen display *vs.* BioPlotter are: Attractiveness 5.29±0.91 *vs.* 5.56±1.16, Novelty 5.48±0.77 *vs.* 6.02±0.69 and Stimulation 5.07±0.91 *vs.* 5.76±0.86, see Fig appx-e.8. Regarding the Novelty of the interface, BioPlotter scored significantly higher than the on-screen display ($p<0.05$). The participants expressed their experience regarding the novelty of the scale: creative, inventive, leading edge, and innovative. The participants rated the Stimulation of the interface with four items: valuable, exciting, interesting and motivating. BioPlotter was also rated significantly higher regarding the stimulation aspect ($p<0.05$). The attractiveness of BioPlotter was slightly higher than on-screen display, but the difference was not significant.

3.6 Qualitative results

The interview was conducted at the end of both biofeedback sessions to collect more insights into the user experience with the digital and physical biofeedback displays. The participants' responses to six open-ended questions in the interview, as listed in Table appx-e.4. We summarized the answers into the following points.

The physical display of BioPlotter is more engaging and attractive than the on-screen display. Most participants (15/20) described the interaction with BioPlotter was a playful and interesting experience. The machine sounds, pen movements and the painting on the paper engaged them with BioPlotter and motivated them to keep on the deep breathing. For instance, some participants commented that "*I* *was attracted by watching it drawing, it was much fun.*" (P3) and "*It seemed that time passed quickly, 10 minutes well spent*" (P10). Several participants (8/20) reported that BioPlotter had some level of playfulness, which reduced the boredom during the biofeedback session. Some of those also expressed an interest in the idea of BioPlotter being available as a device like a 'turntable' for biofeedback breathing training at home. Regarding the on-screen display, most participants (13/20) reported that the on-screen display was clear and easy to observe. Some participants (7/20) stated that it would get a little boring with the on-screen display after a few minutes. They lost their interest in control the display by breathing regulation but instead to observe the digital display passively.

BioPlotter enhanced the bodily experience and enriched the interactive experience. The majority of the participants (17/20) stated that BioPlotter made them more conscious of their heart rate and heart rate variability. They were easily aware of their heart rate through the pen movements. Most participants (14/20) found the machine sounds of the plotter helpful in observing the heart rate changes. Many participants (9/20) reported that the heartbeat-triggered drawing process created a strong sense of connection between the BioPlotter and their body. One participant (P4) expressed that "*the plotter feels like an extension of the body.*" Another said that "*sometimes when I stopped doing deep breathing and just relaxed, I can feel that 'he' was also lazy*." Most participants (14/20) also enjoyed the experience of observing and regulating some aspects of their breathing and heart rate. For instance, one participant (P7) noted that "*the feeling of controlling the machine with my heartbeat and breathing is enjoyable.*"

The physical visualizations by BioPlotter could motivate users to perform better in the breathing training. The physicality and aesthetics of the physical visualizations were two important motivational factors. BioPlotter brought the participants many expectations for the created physical paintings. Most participants were concerned about the appearance of the painting once the plotter started to work. One participant (P11) stated that "*it is exciting to watch the pen drawing lines with my heartbeat, and to predict what it would look like in the end*." According to this participant, he was expecting to see a beautiful 'flower-like' painting, and this kept him motivated in breathing training. The goal of creating a beautiful painting became a strong motivation for them to regulate their breathing into a slower and deeper pattern. This revealed some evidence of the physical displays' motivational potentials on biofeedback self-regulations. The participants also reported the created painting was a good 'reward' for their breathing training. As they received their paintings, the reactions of most participants were positive, e.g., pleasant surprise about the aesthetics, sense of uniqueness, sense of accomplishment.

The design of BioPlotter still has two main demerits. Firstly, some participants reported that sometimes the mechanical arm and the pen would disturb their vision of the physical visualizations on the paper. Secondly, the mechanical sound affected the user experience significantly. For instance, three participants reported a feeling of unease or tension when they first heard the plotter made the whooshing sound with their heartbeat. A few participants reported that the machine sound was amusing at first but became unpleasant even annoying over the time of interaction. They suggested to reduce the machine sound and design a more pleasant or musical sonification of the bio-data to mask the original plotter sound.

4 Discussion

In this design, we used the pen plotter for physical biofeedback display. BioPlotter offers a physical visualization in which the physical paintings replace digital pixels. In the user study, the same visualization design was applied to BioPlotter and an equivalent on-screen display. We compared the physical and digital displays regarding the effectiveness of breathing training and user experience. The results show that the breathing training with both biofeedback displays can improve the participants' heart rate variability. Regarding the user experience, the BioPlotter was rated significantly higher on the scales of Novelty and Stimulation. The interview responses indicate that physical display of BioPlotter is more engaging. BioPlotter may enhance the bodily experience and enrich the interaction with the physical pen movements. Moreover, the physical visualizations may motivate the participants to perform the breathing training better.

Although the accuracy and the dynamic property of the plotter are limited, the pen movements and the physical paintings still possess two valuable features that can be used in everyday biofeedback design. Firstly, the physical movements of the interface can be used to enhance the user's bodily experience. Physical displays offer more parameters (kinetic and expressive) to couple with the bio-data. The physiologically-driven expressions of the interface may lead to a direct connection between the interface and the user's body, enhancing the bodily experience. For instance, in BioPlotter, the participant's heart rate is mapped to many parameters, including the timing, speed, distance of the pen movement and the length of lines in the painting. As such, the heartbeat-triggered physical display greatly enhanced the participant's experience of heart rate variations.

Secondly, the physical visualizations may support both feedback and motivation for biofeedback training. BioPlotter not only presents the concurrent feedback but also visualizes the data into a physical painting, which may act as a terminal feedback at the end of the biofeedback session. Physical visualizations can be powerful motivators in everyday self-regulation practice. As suggested by Munson & Consolvo (2012), physical rewards motivate behavior change inherently. The results of our evaluation also revealed some anecdotal evidence of the BioPlotter' motivational potential and influence on breathing training. The participants were more active and interested in creating a physical painting. We think the motivational potential of physical visualizations can help the users engage with a long-term biofeedback training program.

Typically, in the context of stress management, the audio-visual signals for biofeedback displays are expected to be sedative, fostering a relaxing and calm experience. The interaction with the BioPlotter seemed relatively playful and stimulating and may cause some experiences that are opposite to relaxation and calm. For instance, the fast actions of BioPlotter made some participants feel like being more active and even tense sometime when their heart rate increased. We acknowledge that the heartbeat-triggered motion of the prototype BioPlotter may not apply to the relaxation-purposed applications, such as meditation, yoga, and mindfulness practices. To overcome this concern we might suggest a new breathing-control interactive mode or a slow-paced movement can be implemented with the BioPlotter. As suggested by Šimbelis et al. (2014), a machine with a slow movement might bring more relaxation to those interacting with it. Lehrer & Vaschillo (2008) suggest that the 0.1 Hz slow movement rhythm may stimulate the deep breathing for relaxation.

Besides, BioPlotter still faces some technical challenges. The plotters work slowly because of the mechanical movement of the machine. Moreover, this limits the updating rate of the displayed data. The physical rendering requires specific types of pen and paper. Moreover, the machine sounds are hard to eliminate. However, we think if addressed appropriately in specific context, these challenges can turn out to be valuable factors in aesthetics and interaction.

5 Dissemination and Spinoff

The user study in the Lab uncovered the engaging and motivational potentials of BioPlotter. In complement, BioPlotter can also stimulate the bodily experience and create a personal painting as a material reward. As shown in Fig appx-e.9, the prototype BioPlotter has been adapted for the public exhibitions as an interactive biofeedback installation. The potentials of BioPlotter are further investigated and developed for different intentions: personal Bio-Art creations and charitable fundraising. The public exhibitions are normally crowded with many visitors, and each visitor only has a short time to interact with the installation. BioPlotter has been simplified by using the IBI data as the single input. The installations focus on amplifying and visualizing the natural heart rhythm of the participants. We removed the normalization step to highlight the uniqueness of each dataset.

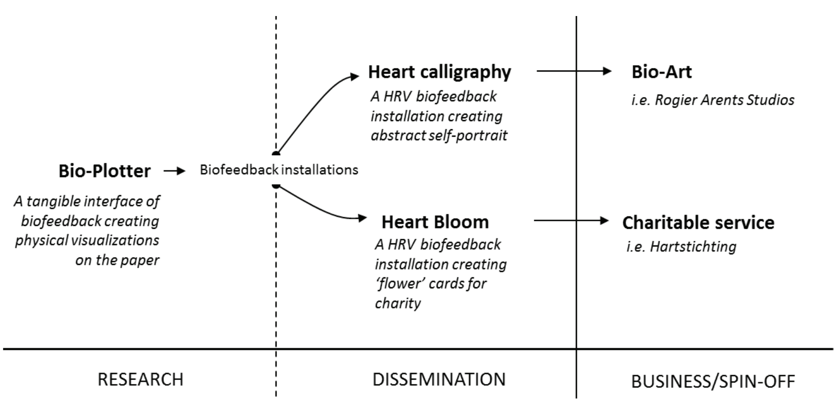


Fig appx-e.9
The dissemination and spin-off based on BioPlotter

5.1 Heart Calligraphy installation for creating a new form of Bio-Art

In the project of Heart Calligraphy, BioPlotter was transformed into an art installation, which aims to 'magnify' the bodily experience of the natural heart rhythm and create a new form of self-portrait reflecting the 'inner self'. The plotter still works upon the heartbeat-triggered action pattern, where the pen acts upon each heartbeat. Drawing upon the inspirations from the oriental calligraphy, "*calligraphy is a silent reflection of the mind, and the mind always leads the brush*," we envisaged to convey a similar idea that "*let the heart lead the brush.*" As a participatory biofeedback installation, Heart Calligraphy invited the participants to stay relaxed and try to 'experience' the subtle variations in their heartbeats along with respiration. Instead of creating the 'flower-shape' painting, it visualizes the participant's three-minute heartbeats data into an abstract portrait, using the changes of the simplest lines and dots to represent the unique heart rhythm of each participant.

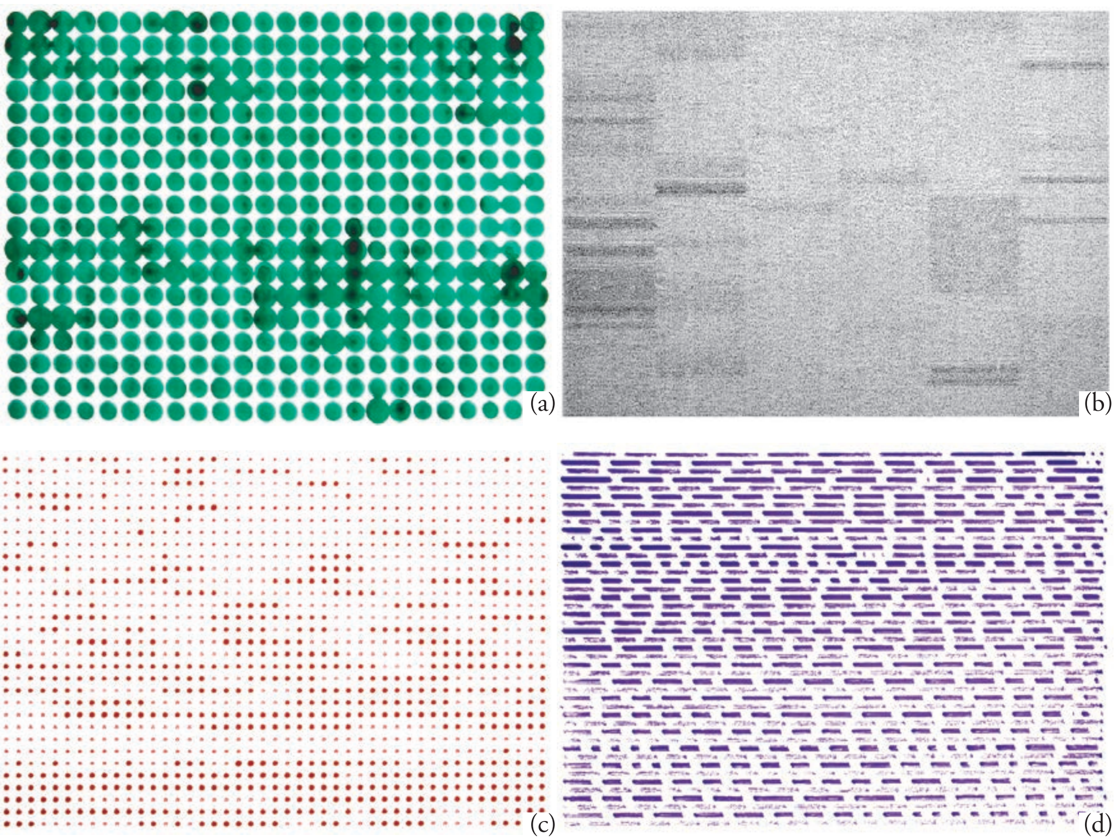


Fig appx-e.10 Abstract drawings created with different physical renderings (a) by a pipet with inkjet ink on watercolor paper (b) by charcoal on sketch paper (c, d) by a felt pen on watercolor paper

Fig appx-e.10 shows a group of abstract paintings of Heart Calligraphy. The paintings represent the heart rate rhythm with different texture effects. Each painting is a personal and unique 'self-portrait'. Physical renderings turn the pen movements into a printed visual presentation in real time. The actions of Heart Calligraphy are quite simple, while the physical renderings play the leading role. Here we explored different physical renderings to present the information in a more artistic and hedonic way.

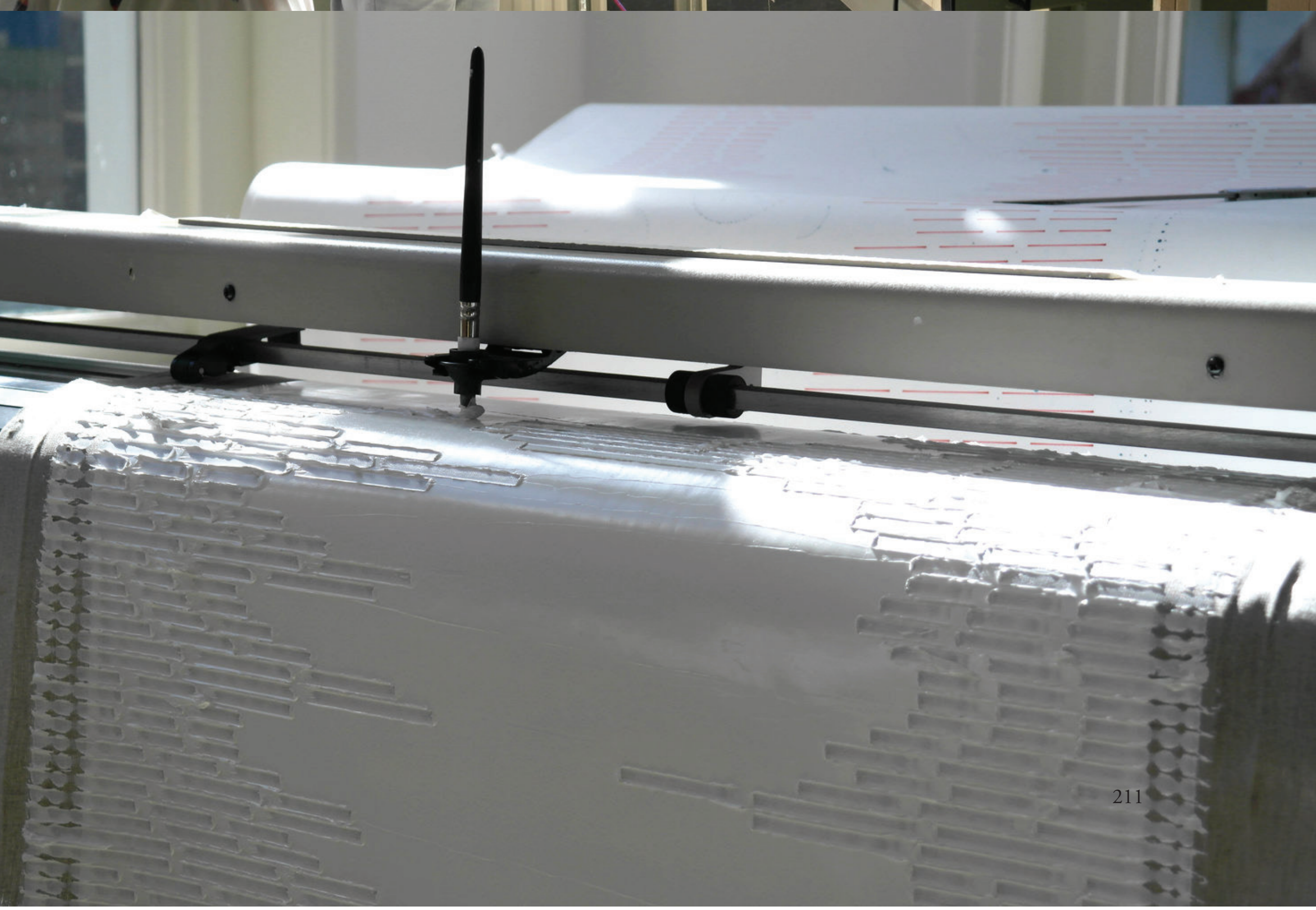
We collaborated with Rogier Arents, a visual artist, to experiment with the visual effects of different painting brushes, materials, and paper. We have two purposes in these explorations. One is to magnify the minor variations of the physical movement into a perceptible visual presentation by making use of the friction between pen and paper or other materials. The other is to deal with the aesthetical aspects of the visual effects. The painting in Fig appx-e.10(a) was created by mapping the IBI data to pen-down time, with a pipet with inkjet ink on watercolor paper. It features round ink spots in the similar size but with different texture and darkness. The sketch in Fig appx-e.10(b) is composed of a series of lines of equal length in rows. The pressure of the pen (charcoal) was adjusted according to the updated IBI data. The real-time heart rate changes are reflected by grey blocks of different in size and shade. Pen-pressure mapping also creates the painting in Fig appx-e.10(c), but with a felt pen on water paper. It features round ink spots in the different size and darkness.

Fig appx-e.11 The installation of Heart Calligraphy and its created charcoal sketch

Heart Calligraphy was installed in *No Particular Order*, Dutch Design Week, Eindhoven, 23th-30th October 2015. Each participant interacted the installation for 3-5 minutes. The participant stood in front of the installation with the PPG sensor on the finger. Then we turned on the plotter and left the participant alone. The participant could see and hear the pen movements triggered by his/her heart beats. Meanwhile, a sketch or watercolor painting was gradually created on the paper. Besides, in Studio Rogier Arents[1], August 2017, a first double-portrait was created for the exhibition *Symbiosis* in the museum *Cognac-Jay* in Paris. It is a response to the portraits of Ernest Cognac and Marie-Louise Jay. As shown in Fig appx-e.12, Rogier and Asnat faced each other, wore the PPG sensors on the finger, stood in front of a large-format pen plotter. The portrait depicted the heartbeat activities measured from the couple and transformed their heartbeats data into an abstract painting with oil on canvas. The painting consists of two columns of simple line graphs, in which each line drawn by one heartbeat. The two sides of line graphs 'embrace' each other and 'celebrate' each other for love.

1. Studio Rogier Arents: www.rogierarents.com/, retrieved:13-11-2017.

Fig appx-e.12
Rogier and Asnat faced each other, wore the PPG sensors on the finger, stood in front of a large-format pen plotter.



A double portrait of Rogier Arents & Asnate Bockis,
70 x 90 cm, Oil on canvas

5.2 HeartBloom Installation for charitable fundraising

In July 2016, with the support of the Design United (DU) and Hartstichting (Dutch Heart Foundation), the prototype BioPlotter has been transformed into the HeartBloom installation which visualizes the participants' heartbeat rhythm into a 'flower' painting on small cards. The mapping between the heartbeat data to the flower pattern is described in chapter 4, section 4.4. HeartBloom installation serves as a charitable initiative for helping children with congenital heart disease (CHD). In public spaces, the interactive installation may quickly grab the public attention and attract the audience to the charitable event. It also offers a good platform to promote charitable initiatives and raise public awareness about the congenital heart diseases. Most importantly, HeartBloom installation enables and enhances the experience of a healthy heart rhythm for each participant to arouse their empathy and caring towards CHD children. A CHD means a child is born with an abnormally structured heart. CHD children are more likely to suffer from heart rate problems such as irregular heartbeats (also known as arrhythmias). For healthy people, in most of the time, their heartbeats show a continually changing rhythm which the CHD children might never experience in their whole life. We believe that if someone can experience a specific situation or what the disadvantaged groups feel, he/she might treat other groups and see public issues in a more empathetic light.

Before the DDW fundraising event, Heart Bloom had been installed first at a few social gatherings of CHD children and their families. We invited more than 50 CHD children to play with the installation, look and experience their heartbeats, see Fig appx-e.13. We collected the CHD children's heartbeat data and the stories that they would like to share with the public during the fundraising event. A collective painting was made with the CHD children's HeartBloom drawings and later exhibited to the public, see Fig appx-e.14. The collected stories were used in the creation of the storyboard, which is integrated into the user interface of the installation.

Fig appx-e.13
A group of CHD children playing around the HeartBloom installation

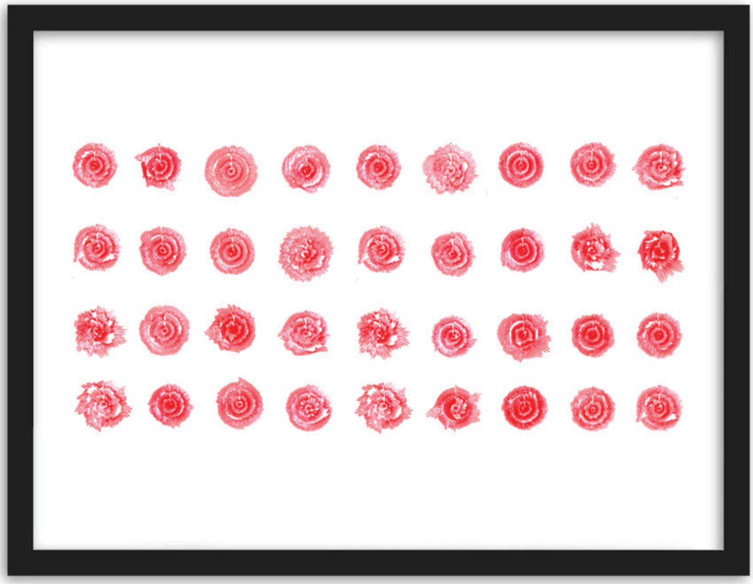


Fig appx-e.14 the collective painting created by the CHD children

The major Heart Bloom fundraising event was held at one of the leading exhibition halls in Eindhoven during DDW from 22nd to 30th October 2017. The goal was to invite more than 500 participants to experience the installation and make a large collection of 500 HeartBloom drawings during the 9-days event. The participant stood in front of the installation stand, facing the pen plotter and a touch-screen tablet which runs the heart bloom program. The participants first entered their name and email address on the launcher page of the program and then placed the PPG sensor on a finger. After detecting the valid heartbeat data, the installation started working. During the interaction, the storyboard was automatically played, and the heartbeat data was stored in a local file with a unique label of the participant's email address. With the drawing done, the participants hung their created HeartBloom card in the wooden frame. After the interaction, on the website of Heart Bloom, the participants could search their HeartBloom with their email address. By making a small amount of online donation (5-15 euro), the participant can order a reprint of their HeartBloom painting on a postcard or a gift card.

During the DDW fundraising event, a total of 823 participants interacted with the HeartBloom installation. HeartBloom greatly inspired enthusiasm and improve the engagement of the participants with the charitable activity. HeartBloom installation triggered the bystanders to participate in the event. The amount of the participants turned out to be greatly larger than we expected. Because only one participant could interact with the installation at a time, the participants often needed to queue up and waited about 20 minutes. The stimulated enormous enthusiasm was also shown by a wide range of the participant's age and background. The youngest participant is a four-month baby, and the oldest participant is eighty-sixed years old. Dutch royal family has also joined the event. Within two weeks after the event, 105 online donations (the total amount is 1150 euro) were received. Overall, 10% of the participants donated with an average of €10.

Fig appx-e.15
The participants around the HeartBloom installation

Fig appx-e.16
The youngest participant interacted with HeartBloom at DDW charitable fundraising event

The DDW event gave us a different lens to think about the engaging and motivational potential of BioPlotter as a participatory, interactive installation for charitable fundraising. We found that the tangible installation can be effective in attracting the passerby move to and stay at a public event. The physiologically-driven drawing process was new to most of the participants. Most of the participants stated that they had never experienced their heartbeat with an external machine. To gain this novel experience became a big motivation for the bystanders to participate in actively. The physical paintings have a strong appeal to the participants due to its uniqueness and individuality. The flower pattern not only depicted the temporal uniqueness of a piece of heartbeat data in one's life, but also the physiological uniqueness of each heart among others. As shown in Fig appx-e.15, lots of the participants showed a great interest in observing, comparing and identifying the difference between the flower patterns.

Despite a high enthusiasm and numerous participants in the event, the number of online donations did not reach our expectation. In our view, the possible reasons are the online donation required an extra effort from the participants. For the DDW event, we found a large percentage of the participants were children, teenagers, elder people, and the visitors from abroad. The online donation increased the difficulties for them to complete. At the DDW event, we had not accepted the on-site donations. Instead, the web link of the online platform was sent to the participants later via email. The participants' enthusiasm for the donation was probably reduced with the extension of time.

To overcome these deficiencies, a mobile HeartBloom mobile application has been developed with some modifications to simplify the system set-up and increase the efficiency in fundraising. Firstly, we replaced the tangible installation with a light-weight, self-contained mobile application, which is easier to operate and maintain. The HeartBloom application captures heartbeat data with a phone's camera and visualizes the flower pattern interactively on the screen. The participant places his/her finger on the camera lens during the interaction, as shown in Fig appx-e.17. Secondly, during these street fundraising events, after the participants created the digital flower pattern, they were given an option to print it on a postcard by making a donation. Here, the participants can skip the online platform and complete their donations immediately on the site by cash or credit card. The participants took their printed postcard directly without the need for extra mailing service.

As shown in Fig appx-e.17, the HeartBloom APPs are installed on the service cart, serving as a mobile 'fundraiser' in long-term use. The HeartBloom mobile 'fundraisers' have been used for several public events, including the *Libelle's Zomerweek*, *De 50+ beurs*, *Albert Heijn* sport event, and *Philips connect-run*. Overall, 75% of the participants donated with an average of €2,50. Compared to the DDW event, the ratio between the participants and the final donators were significantly increased, probably due to the simplification of donation procedure and pressure of the volunteer. The average amount of each donation decreased because no service cost is required from the external service providers.

Fig appx-e.17 HeartBloom mobile 'fundraiser' working on the street for Dutch Heart Foundation

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When I graduated from primary school,
my parents took me to a photo studio
and dressed me like a real Ph.D.
At that moment,
a doctoral degree was a dream to my family.
Today,
this work is dedicated to my families.

献给我的家人

瀑布的水逆流而上,
蒲公英的种子从远处飘回，聚成伞的模样,
太阳从西边升起，落向东方。

子弹退回枪膛,
运动员回到起跑线上,
我交回录取通知书，忘了十年寒窗。

厨房里飘来饭菜的香,
你把我卷子签好名字,
关掉电视，帮我把书包背上。

你还在我身旁

—戴畅<你还在我身旁>

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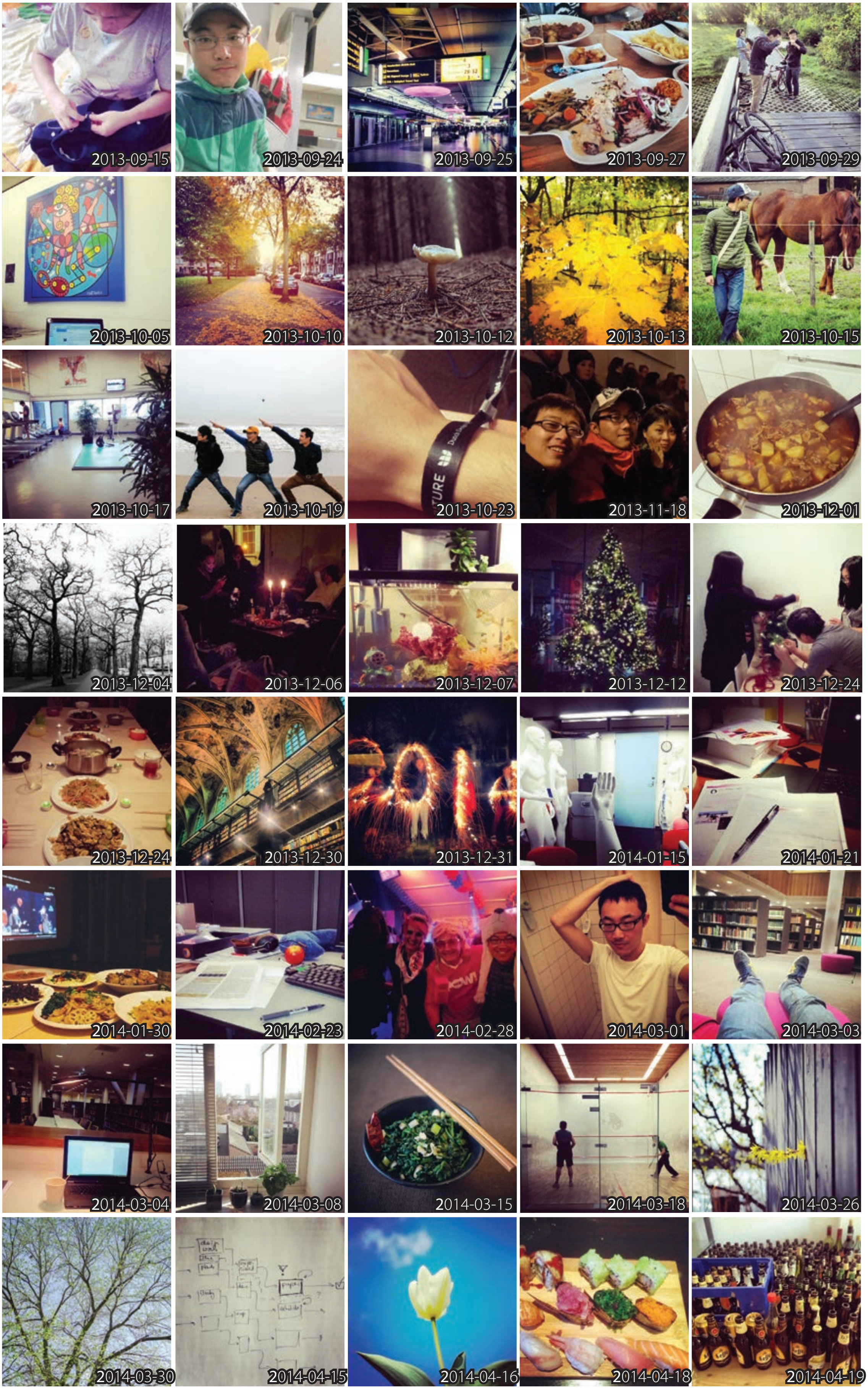
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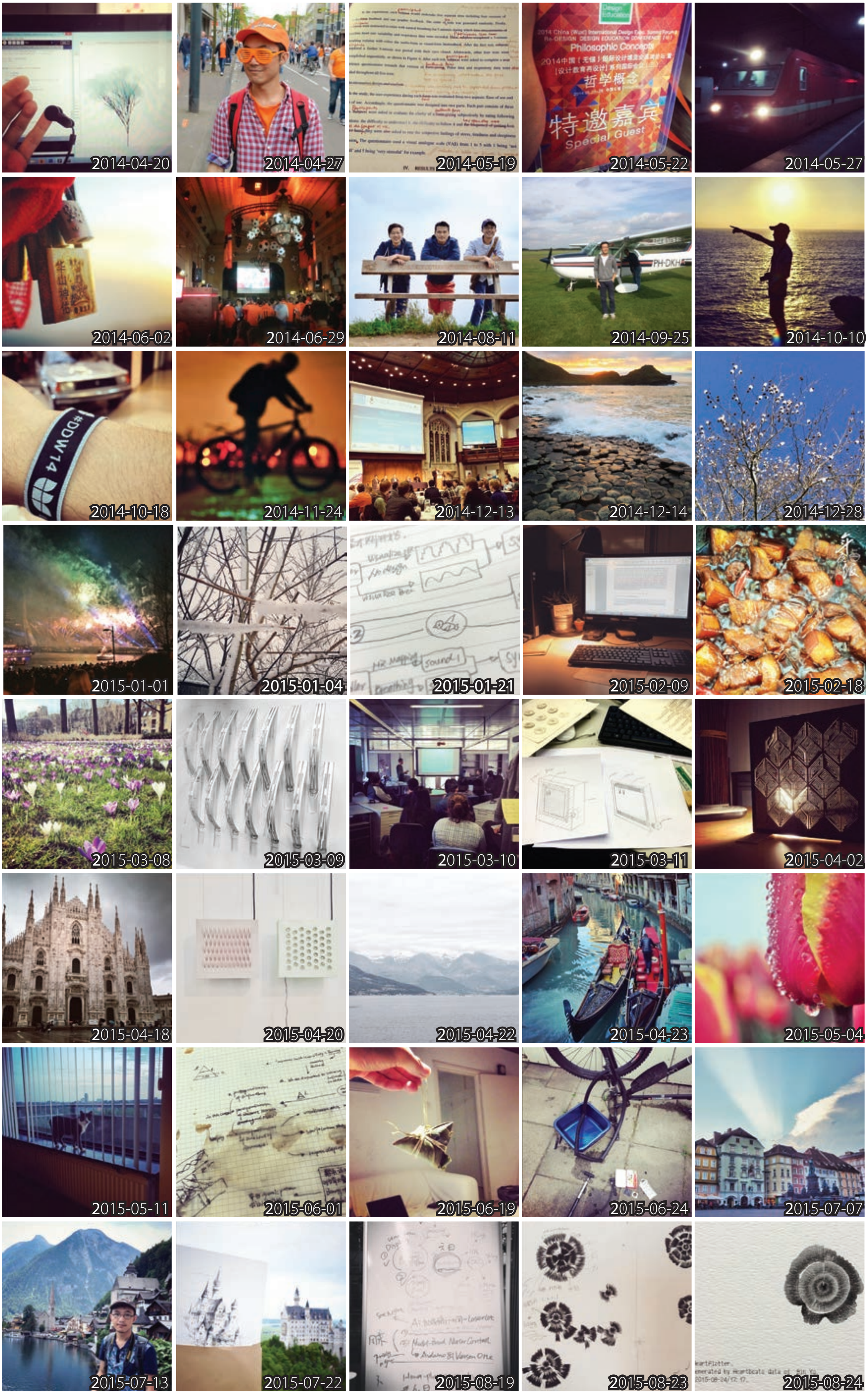
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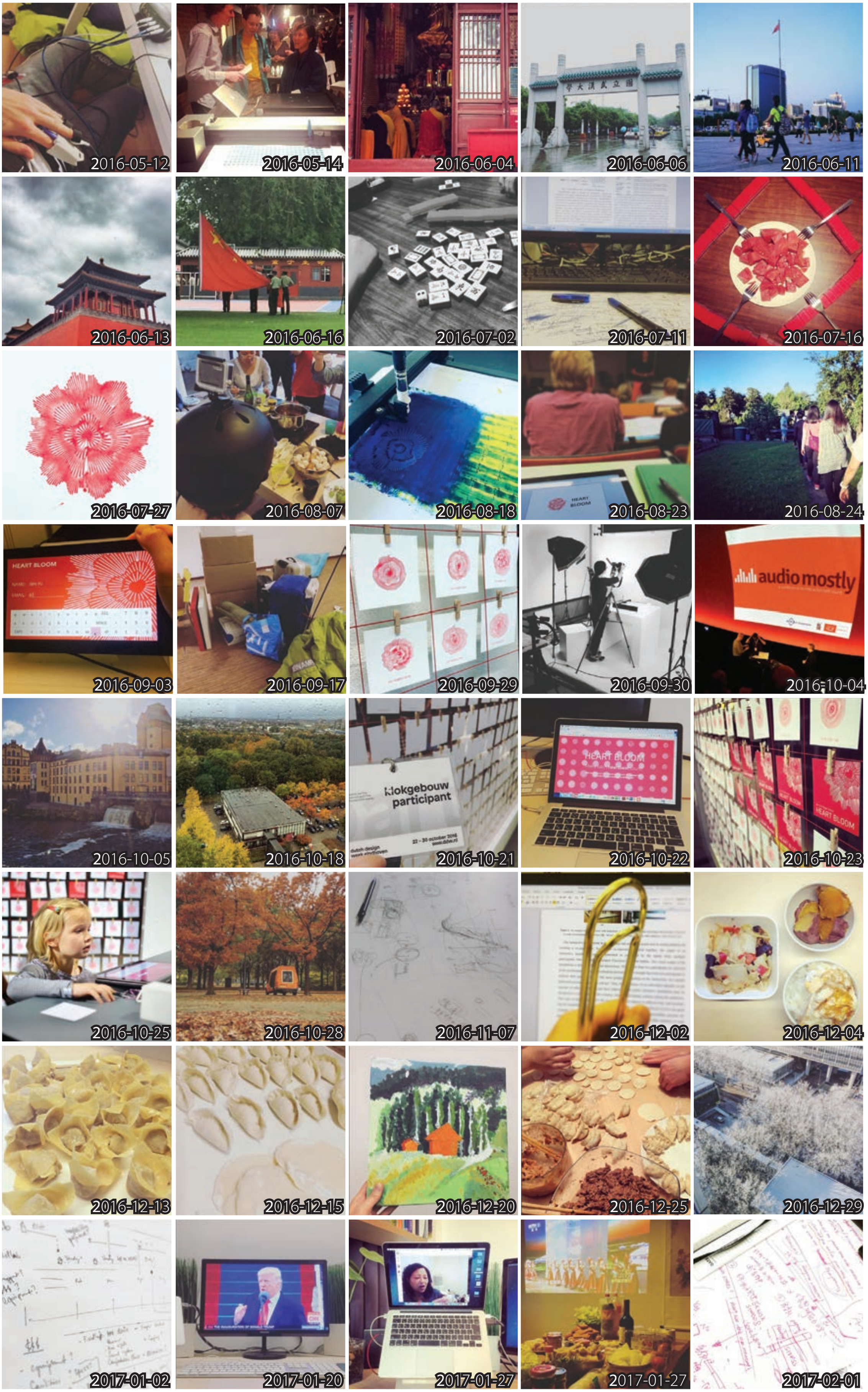
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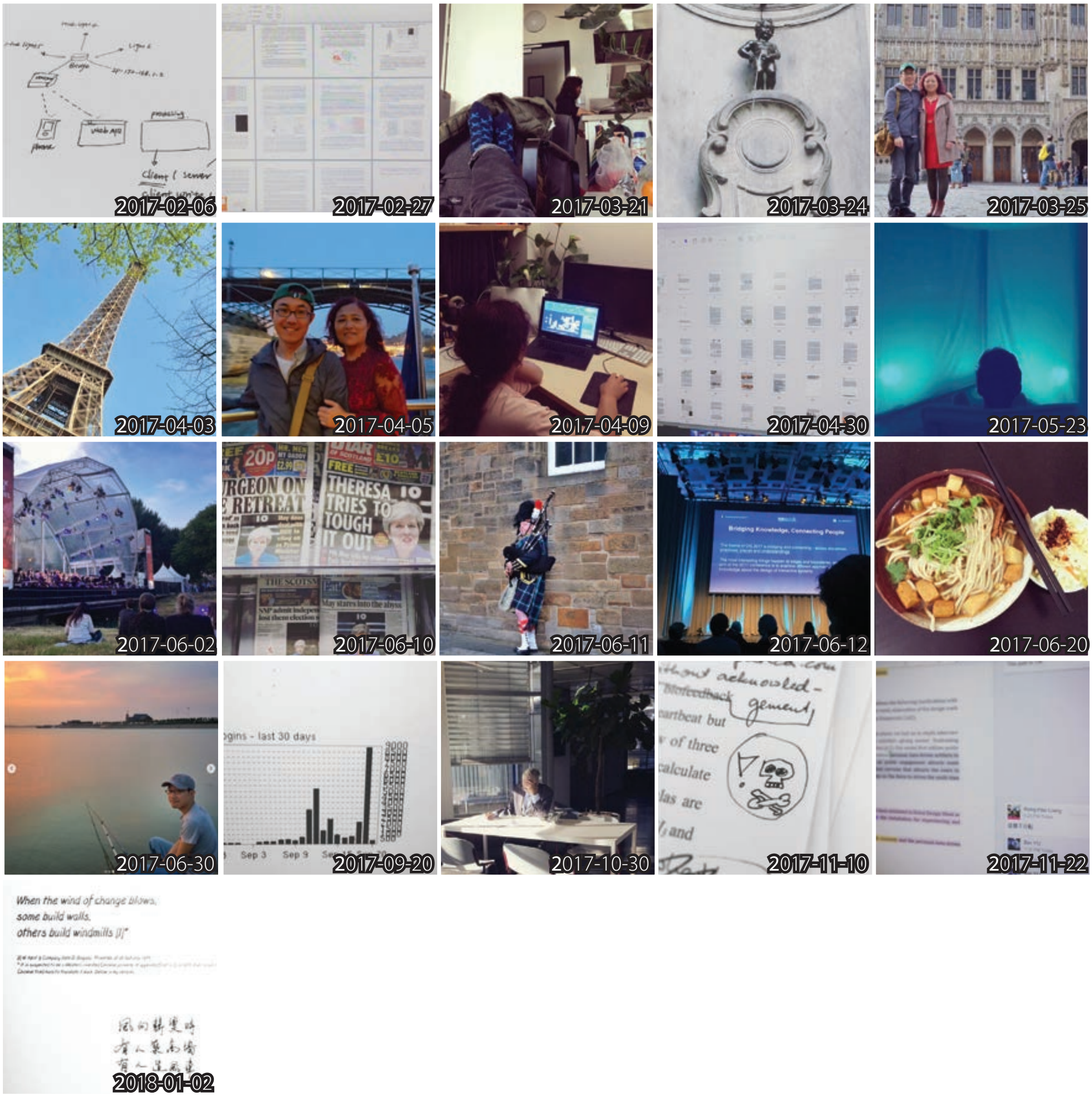

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BIN YU

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Curriculum Vitae

Biography

Bin Yu was born on the 25th of January, 1988, in Nei Mongol, China. In 2010, he received the double bachelor degree in Biomedical Engineering and Industrial Design at Chongqing University in China. Next, he was recommended for admission to Northeastern University, Shenyang, China. He started a master program of Mobile Healthcare Design at Sino-Dutch Biomedical and Information Engineering School and obtained the Master degree in 2012. After graduation, he worked as a research assistant in the Institute of Biomedical and Health Engineering, SIAT, Chinese Academy of Sciences.

In October 2013, he started his Ph.D. research in the Industrial Design department of Eindhoven University of Technology. The Ph.D. project was carried out under the supervision of prof. Loe Feijs, dr. Jun Hu and dr. Mathias Funk. This thesis is the result of his Ph.D. research on the topic of "Designing Biofeedback for Managing Stress".

Publications

Journals

1. Yu, B., Hu, J., Funk, M. and Feijs, L. (In Press) Delight: Lighting Biofeedback for Stress Management. *Journal of Personal and Ubiquitous Computing*
2. Yu, B., Funk, M., Hu, J. and Feijs, L. (In Press) UnWind: Musical Biofeedback Interfaces for Relaxation Training. *Journal of Behaviour & Information Technology*.
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Exhibitions

- 'HeartBloom for Charity', at Mind the Step, Dutch Design Week, October 2016
- 'Double-portrait' at the exhibition Symbiosis in the museum Cognac-Jay, September 2016
- 'HeartBloom & Heart Calligraphy', at the WantedDesign, New York Design Week, May 2016
- 'BioMirror', at Global Grad Show, Dubai Design Week, November 2015
- 'BioMirror', at Mind the Step, Dutch Design Week 2015
- 'Heart Calligraphy', at In No Particular Order, Dutch Design Week 2015
- 'Dialogue', at Dutch invertuals, Milan Design Week, April 2015

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