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ORIGINAL ARTICLE

DeLight: biofeedback through ambient light for stress intervention and relaxation assistance

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Abstract
Light is a common ambient medium to express additional information in a peripheral and calm way, but it is also an environmental stimulant to create atmosphere, evoke moods, and provide immersive experiences. Through the design of the *DeLight* system, we aim to establish a biofeedback-driven lighting environment that informs users about their stress level for intervention and assists them in biofeedback relaxation training. In this study, *DeLight* is interfaced with a heart rate variability biofeedback system with two modes for different purposes: stress intervention and relaxation assistance. We evaluated the prototype of *DeLight* in two user studies. The results of the first study show that *DeLight* has the potential for stress intervention; the HRV biofeedback through the changes of ambient light could improve a user's awareness of stress and trigger behavioral conditioning, such as deep breathing. The results of the second study confirm that *DeLight* has potential as a new biofeedback interface for relaxation assistance; biofeedback through an immersive lighting environment can support physiological regulation as effectively as graphic biofeedback; it offers enhanced relaxation effects regarding both subjective experience and physiological arousal. These findings suggest that the biofeedback-driven ambient light can perform as persuasive technology in the domain of health self-management. The combination of decorative and informative aspects enables the lighting interface to offer the users a comfortable and relaxing condition for biofeedback-assisted relaxation training.

Keywords Biofeedback · Ambient display · Lighting interface · Stress management · Relaxation

1 Introduction

Since Weiser (1991) coined the term *Ubiquitous Computing* [1], the idea of a peripheral and more environmentally integrated way of information display has been appealing to many researchers and designers in the human-computer interaction (HCI) realm. *Ubiquitous Computing* envisioned a new paradigm of HCI which attempts to push computers into an "invisible background." Weiser and Brown (1997) further formulated *Calm Technology* [2], which suggests that the information display should move easily from the periphery of our attention to the center, and back. In the following decades, the vision of *Ubiquitous Computing* inspired many research communities, e.g., around ambient displays [3], information decorations [4], and peripheral interactions [5].

Ambient displays present information in the periphery of people's attention for less distracting or burdening them. Ambient information systems can be "always-connected" to data sources, communicating information calmly through the subtle changes in an architectural space [6, 7], decorative objects [8, 9], sound [10], or ambient light [11]. These displays tend to be esthetically pleasing and seamlessly merged with a physical environment, where various everyday objects are turned into an interface between people and digital information. One of the best-known examples is *ambientROOM* [12], a physical architectural space supporting peripheral awareness of information with light patches on the wall, natural sounds in the background, and water ripples projected on the ceiling.

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As a common means of ambient display, light is not only rich in parameters for portraying information but also can evoke moods and create immersive experiences. This work started at the intersection of ambient lighting displays, biofeedback techniques, and *Calm Technology* [2] in the context of stress management. We developed an ambient biofeedback system named *DeLight*, which implements biofeedback that is conventionally provided via a GUI of desktop PCs in an ambient interface of light. *DeLight* was designed according to the principles of *Calm Technology* [2], offering two working modes for both peripheral stress intervention and immersive relaxation training. Two user studies were conducted to investigate each mode regarding (1) the feasibility of ambient light for biofeedback display and (2) the effect of a colored lighting environment on relaxation.

The rest of the paper is structured as follows. Section 2 provides a review of related literature on biofeedback techniques, colored lights for relaxation, and state-of-the-art biofeedback interfaces and lighting displays. Section 3 describes the overall *DeLight* biofeedback system. Section 4 presents the first working mode of *DeLight* for peripheral stress intervention and its evaluation during a simulated stressor. Section 5 presents the second mode of *DeLight* for relaxation assistance and its evaluation during a biofeedback relaxation training. Section 6 discusses the potential of ambient light for biofeedback. Finally, Section 7 closes with conclusions and future directions.

2 Related work

2.1 Stress and biofeedback

In modern society, everyone will run into a variety of stress. Stress responses occur when a situation is perceived to be challenging or threatening (e.g., facing a speeding car). Unfortunately, many chronic stressors, such as traffic jams, work pressure, and family difficulties, keep the stress responses "always-on," causing excess production of the steroid hormone cortisol [13]. Chronically elevated cortisol levels put individuals at an increased risk of numerous health problems, including anxiety, depression [14], immune dysregulation [15], heart disease [16], hypertension [16], and diabetes [17].

Biofeedback is a technique that visualizes a user's internal states and guides the user to control specific physiological activities consciously [18, 19]. With biofeedback devices, the users can observe the negative impacts of stress on their physiology and further to manage stress responses and practice relaxation skills. Figure 1 shows a typical biofeedback diagram for self-management of stress. The user's physiological signals are measured by various bio-sensors and processed by a biofeedback program. Then the ready-processed biofeedback data are mapped to visual or audio representations for display. The user perceives the feedback information through interactive media, decodes the biofeedback information, and applies it in their self-regulation and behavioral conditioning.

Since about 40 years ago, biofeedback techniques have been applied in clinical settings for treating anxiety disorders [21] or post-traumatic stress disorders [22]. These clinical applications are typically performed in a therapy room with the assistance of a well-trained therapist. Recently, efforts from the HCI community popularize the use of biofeedback in people's everyday life. A growing number of "casual" biofeedback systems have been developed to help end-users work on stress management with more flexibly in everyday settings, such as in an office, a resting room or at home. This concept has been called *Ubiquitous Biofeedback* (U-Biofeedback) in [20]. U-biofeedback advances by the research from both physiological computing (blue blocks in Fig. 1) and HCI (red blocks). For instance, advanced bio-sensors enable the measurement of bio-signals to be more unobtrusive, and ambient displays make the feedback information more accessible embedded in the surrounding environment. This work focuses on aspects of HCI design (red blocks) in the biofeedback diagram above and especially explores the emerging role of ambient light for biofeedback display.

2.2 HCI design for ambient biofeedback

In the field of *Ubiquitous Biofeedback*, we see the therapist-mediated clinical biofeedback training being gradually replaced by computer-mediated everyday training, where ambient displays are often used to facilitate information perception and user experience with biofeedback systems. On the one hand, ambient biofeedback can enhance self-awareness in the periphery of the user's attention. For instance, Yokoyama et al. [23] developed a biofeedback system that presents the instantaneous heart rate in the form of music to not hinder work. Moraveji et al. [24] integrated respiration biofeedback into the desktop operating system in a peripheral manner. The user's breathing rate is presented as an animated, semi-translucent gray bar stretching across the screen or as an indicator in the system tray. On the other hand, the ambient displays have its advantages in shaping user experience. For instance, *Sonic Cradle* [25] creates a meditation environment where the user is immersed in a soundscape responding to his or her breathing pattern. In *ExoBuilding* [26], biofeedback data are presented by multiple ambient media—lights, sounds, and the physical space change to immerse users in a relaxation training.

2.3 Lighting interface in HCI

Light as an integral part of everyday settings, is a good ambient media to portray additional information. Its basic

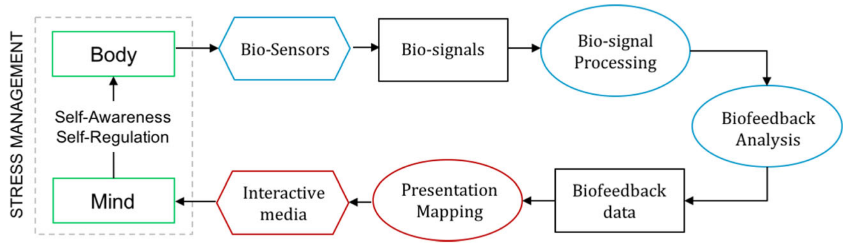

Fig. 1 A typical biofeedback diagram adapted from [20] in the context of stress management

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 esthetically pleasing, decorative, and unobtrusive. For instance, *Ambient Timer* [27] was designed to remind users of upcoming events in office settings unobtrusively. Similarly, Occhialini et al. [11] used lighting displays to support time management during meetings. Maan et al. [28] used ambient light to indicate the energy consumption, which showed a stronger persuasive effect than numerical feedback. Also, office lights can be manipulated by the recent physical activities of the office workers to motivate them to be more physically active [29].

Light, as an environmental stimulant, has a particular ability to create atmosphere, evoke moods, and provide immersive experiences. *Flower Power* [30] projects a set of saturated changing lights on the wall of public space to create immersive experiences for the audience. In *IllumiRoom* [31], 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* system.[1] Besides, light can be a great focus for meditation or guided relaxation. For instance, Ståhl et al. [32] designed an ambient light that dims in cadence with the user's breathing to support a meditative bodily experience.

2.4 Relaxation with light

Several lines of evidence [33–36] 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 [33, 34]. Ross et al. [35] 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 [32]. Colored light therapy [36] 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* created an adaptive relaxation space[2] with ambient lights to help people reduce work-related stress and encourage mindfulness. 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.

Above studies have shown the beneficial effects of light for both ambient displays and relaxation, but little work has explored it for biofeedback in the context of everyday stress management. In a recently qualitative study [37], Snyder et al. investigated the user experience of seeing their internal, affective state represented in an ambient lighting display. They found that the biofeedback of arousal level via ambient light may improve self-awareness and support self-discovery. However, this study has not dealt with the effectiveness of information display. In our prior work [38], we presented a preliminary exploration on ambient biofeedback. A lighting interface has been developed for heart rate variability (HRV) biofeedback. A pilot study has been carried out to assess its effectiveness of information display. The results suggested that the developed light interface was as effective as a typical tachogram of inter-beat intervals (IBI) and could also set a relaxing ambiance for biofeedback training. This paper presents more in-depth research on lighting biofeedback for stress management. We developed a physiologically-responsive ambient lighting environment and examined its feasibility for both peripheral stress intervention and immersive relaxation training.

[1] Philips AmbiLight system, https://www.philips.co.uk/c-m-so/televisions/p/ambilight.

[2] Philips Adaptive Relaxation Space, http://www.crisprepository.nl/project/grip/prototype/relaxation-space.

[3] F.lux software: https://justgetflux.com/

3 Delight biofeedback system

This work seeks to put biofeedback techniques into the "invisible background," where the users can perceive their internal states and perform biofeedback-assisted relaxation training in a calming and comfortable condition, such as sitting on a yoga mat, leaning back in a comfortable chair, or slowly walking around in a room. The design goal of *DeLight* is twofold: (1) an ambient interface for biofeedback display in everyday environments and (2) a lighting environment for an immersive relaxing experience. We believe the combination of decorative and informative aspects can make ambient light both pleasant and helpful for users.

Heart rate variability (HRV) biofeedback [39] is the most commonly used biofeedback technique for stress management. HRV biofeedback enables users to be more aware of their stress responses [40] and improve self-regulation skills to keep the autonomic balance [41]. In this work, *DeLight* is interfaced with an HRV biofeedback system in two modes: stress intervention mode and relaxation assistance mode. In the stress intervention mode, *DeLight* informs the users about their stress level and facilitates them to control the heart rate response or reactivity to the stressful situation. In the relaxation assistance mode, *DeLight* assists the users to practice resonant breathing during relaxation training. The bio-data processing and the design of lighting presentation are adapted for each mode. We elaborate on these details in next sections.

As shown in Fig. 2, *DeLight* biofeedback system consists of three parts: a bio-sensing device, a biofeedback program, and a lighting system. The bio-sensing device is *NeXus10* front-end from *Mind Media.*[4] It is a battery-powered portable device which can measure multiple physiological data including blood volume pulse (BVP), skin conductance (SC), and respiration (RSP). The collected raw data are then transmitted to the PC biofeedback program via a Bluetooth connection. According to different modes, the targeted HRV parameters are calculated as the biofeedback data and coupled with the parameters for lighting control. A set of programmable light bulbs (*Philips HUE*[5]) 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 can be placed freely and held by the users during the relaxation. 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.

[4] MindMedia B.V. Nexus-10. http://www.mindmedia.nl/english/nexus10.php.

[5] Philips Hue: http://www2.meethue.com/nl-nl/.

4 Study one: stress intervention with *DeLight*

Heart rate (HR) and heart rate variability (HRV) biofeedback can be used to train the users to control their heart rate response and reactivity to acute stress. HR biofeedback has proven to be effective in lowering HR, improving HRV and reducing self-reported anxiety [42]. Peira et al. [43] reported that HR biofeedback training could enhance the ability of emotion regulation when participants were exposed to negatively-arousing pictures. Yokoyama et al. [23] suggested that HR biofeedback may help users in improving cardiac control during stressful tasks. In the stress intervention mode, *DeLight* aims to help the users cope with excessive stress responses during a high-stress work. *DeLight* creates ambient awareness on the periphery of a user's attention, informing the user about his or her short-term HR and HRV levels by adapting the color of the ambient lights.

4.1 Biofeedback data processing

The HR and HRV information is calculated from the Blood Volume Pulse (BVP) signal that is measured by a photoplethysmography (PPG) sensor on the user's earlobe. The BVP signal reflects the blood volume changes caused by the contraction of the heart. Detecting the peaks of BVP signal locates the heartbeats in the time domain and results in a sequence of Inter-Beat-Interval (IBI) data. The IBI is the time difference between two heartbeats in milliseconds. Based on the IBI data, two parameters, HR_{avg} and HRV_{40}, are calculated for presentation mapping. We first calculate the short-term averaged heart rate (HR_{avg}). As deep breathing (e.g., six breaths/min) can cause an obvious oscillation of heart rate, the HR_{avg} is calculated based on a moving window of 16 heartbeats to minimize the impact of breathing cycles. IBI_{16} denotes the average of IBI in the window: $IBI_{16} = (15 \times IBI_{16} + \mathrm{IBI})/16$. The IBI_{16} is measured in milliseconds, and its initial value is 600 ms. So the HR_{avg} is obtained by using 60,000 divides IBI_{16} value. Next, we calculate the SDNN (the standard deviation of IBI data) in a moving window of 40 IBIs as the short-term HRV index. SDNN is one of the most common time domain indices of heart rate variability, reflecting overall autonomic nervous system (ANS) activity. In the calculation of real-time HRV_{40}, we use the following formula: $HRV_{40} = ((39 \times HRV_{40} + |\mathrm{IBI} - IBI_{40}|)/40)$. The IBI_{40} is calculated in the same way as IBI_{16}. The HR_{avg} and HRV_{40} are updated with each heartbeat and mapped to the lighting parameters as described next.

4.2 Presentation mapping for lighting display

In study one, *DeLight* system was mainly applied to help participants cope with the mental workload. To minimize the interference of light changes on the work, the brightness of

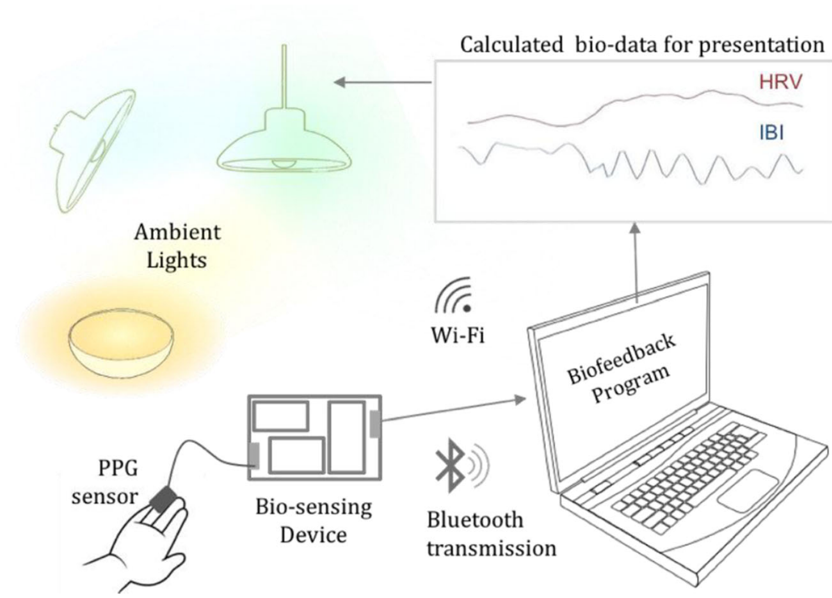

Fig. 2 System framework of *DeLight* biofeedback system

lights remains the same while the biofeedback data adjust the color of lights within a limited range. Here, we encountered an issue when attempting to select an appropriate color to present the biofeedback data. Color has psychological and physiological effects on us. Red is associated strongly with danger and tension, while blue or green is often associated with calm [44]. In the perspective of information display, red or orange color can better represent a warning sign of high stress. However, regarding the user experience, red, orange or other long-wavelength colors might be more arousing and even tense. Instead, a short-wavelength color, such as cyan or blue, can evoke more pleasant and calm feelings [45, 46]. We wondered how users would feel when the lights are turning orange or even red due to their increased stress and whether they would feel more stressed by such a "warning" orange light. On the contrary, we can also use a cool-toned color; for example, the lights turn green or blue when the users are stressed. However, the question is, whether the "calming" light can effectively inform and motivate the users to initiate the stress management. We leave this dilemma to the user study, in which two color mappings (warm vs. cool) were designed and evaluated.

As shown in Table 1, the hue of lights is coupled with HR_{avg}, and the saturation is coupled with HRV_{40}. In warm-toned mapping, the colored light works as a warning sign of increased stress responses. The light turning orange indicates an increased HR and decreased HRV (see Fig. 3b). The HR_{avg} is mapped to the value of hue ranging from 12,750 (yellow) to 14,000 (orange). In cool-toned mapping, the light works more like an ambient stimulus to induce relaxation when the user becomes stressed. The HR_{avg} is mapped to the value of hue ranging from 40,750 (cyan) to 46,920 (blue) (see Fig. 3c). In both color mappings, the HRV_{40} is mapped to the saturation parameter of lights ranging from 150 to 20 (the maximum is 255, the minimum is 0). In the same hue, the higher the saturation is, the darker the color is. The decreased HRV under a stressful situation will lead to a dark color of light, which might attract more attention of the users. The presentation mapping and light rendering are updated with the heartbeats.

4.3 Evaluation

This experiment attempts to examine the feasibility of *DeLight* for stress intervention. The participants who performed a timed arithmetic task using computers were exposed to the *DeLight* system. We hypothesized that the biofeedback through *DeLight* improves the participants' awareness of their stress level and further motivates them to manage stress under mental workload. As shown in Fig. 3, the *DeLight* system was installed in a personal office room (width, 2.5 m; length, 3.5 m), which consisted of a chair, a desk, a carpet, a plant, and several whiteboards to diffuse and reflect lights. The desk stood against the wall. The center light was placed behind the computer screen. One ambient lamp projected light on the whiteboards behind the user and the other lamp was hung from the ceiling.

Table 1 Presentation mapping from biofeedback data to lighting parameters in stress intervention mode

Biofeedback data	Cool-toned mapping	Warm-toned mapping
Averaged heart rate (HR_{avg})	Hue: cyan-blue (40750–46,920)	Hue: yellow-orange (12750–14,000)
Heart rate variability (HRV_{40})	Saturation (150–20)	Saturation (150–20)

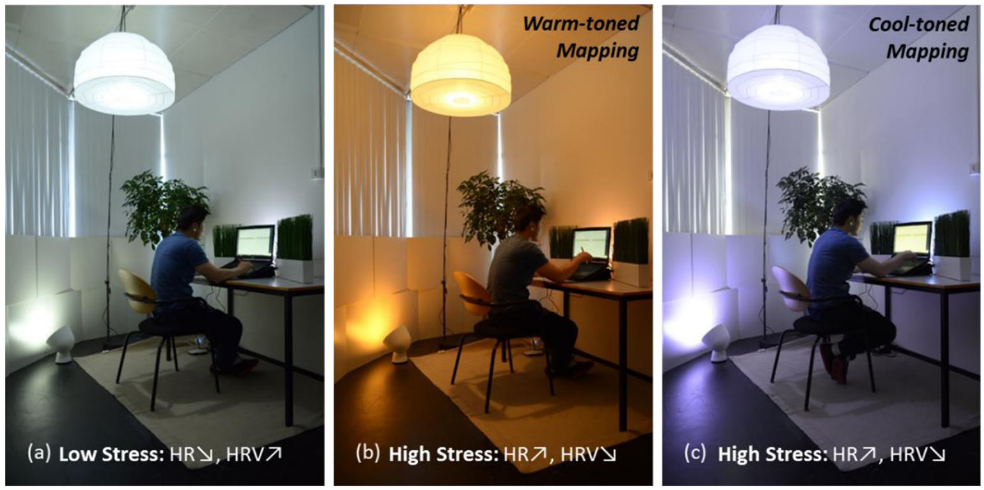

Fig. 3 The effects of *DeLight* when the participant was undergoing **a** low stress, **b** high stress in warm-toned mapping, and **c** high stress in cool-toned mapping

4.3.1 Experimental protocol

Twelve participants (six females and six males, age range 25 to 35 years) took part in the experiment through informed consent procedures. They were all from research-related positions at university. All participants complete an online arithmetic test under three conditions: (1) control condition with no biofeedback, (2) warm-toned lighting biofeedback condition, and (3) cool-toned lighting biofeedback condition. The arithmetic test was a fast-paced speed drill where the participants were given 5 min to solve as many arithmetic problems as they could.

The procedure of the experiment is shown in Fig. 4. Before the experiment, the participant sat on the chair and was fitted with the PPG sensor on one earlobe. The participant relaxed for 5 min, during which we collected the baseline of physiological data and subjective stress ratings before attempting the arithmetic problems. For biofeedback mapping, the range of HR and HRV were measured for each participant. The participant first relaxed with deep breathing for 1 min, during which the average heart rate and overall SDNN were calculated as the minimum HR and the maximum HRV. Next, the participant did 1-min physical exercises. We calculated the average HR and overall SDNN of the following 1-min, as maximum HR and the minimum HRV. In biofeedback program, the individual range of HR and HRV of each participant were mapped to the range of lighting parameters for biofeedback display.

The experiment followed a within-subject design with counterbalancing to avoid carry-over effects. Between the tests, the participant rested for 3 min. Before the arithmetic test, the participant was given the following instructions about the task: "When the lights become bright, and you can start the arithmetic test. It will take 5 minutes; please try to figure out these arithmetic problems as many as possible". Before the tests under two biofeedback conditions, an extra instruction about the lighting feedback was given: "When your stress level becomes high, the color of light might become ORANGE/BLUE. Try to relax yourself to influence the light return to the original color".

4.3.2 Measurement

Firstly, for each participant, the IBI data were collected during each test. The average HR and overall HRV(SDNN) were then calculated through the analysis of the IBI dataset in *Kubios* software.[6] SDNN is the standard deviation of the IBI. It reflects all the cyclic factors that contribute to heart rate variability during the period of recording; therefore, it represents total variability. In long-term ambulatory recordings, HRV reflects the autonomic activities, which are related to the bodily stress responses [47]. Several studies, e.g., [48] suggested that when an individual is under stress, anxiety or panic, the parasympathetic activities tend to be suppressed, resulting in a decreased HRV. While in short-term recordings, HRV might be highly related to the respiratory cycle of the participants [49]. Deep breathing can enhance HRV quickly. Therefore, in this study, SDNN serves as the criteria of the biofeedback effects on self-regulation (mainly related to deep breathing) during the stressful task. Secondly, after each task, the participants were asked to rate his/her subjective feeling of stress on a nine-point rating scale with one being "Not at all" and nine being "Feel it very much." Thirdly, after each test under biofeedback condition, the participants were asked to evaluate the lighting display by rating the following three questions on a nine-point scale: (1) *To what extent did you notice the changes of lights during the test?* (2) *To what extent the changes of lights made you think of your stress level?* (3) *To what extent the lighting environment made you feel calm or relaxing?*

[6] Kubios HRV Analysis Software: http://www.kubios.com/.

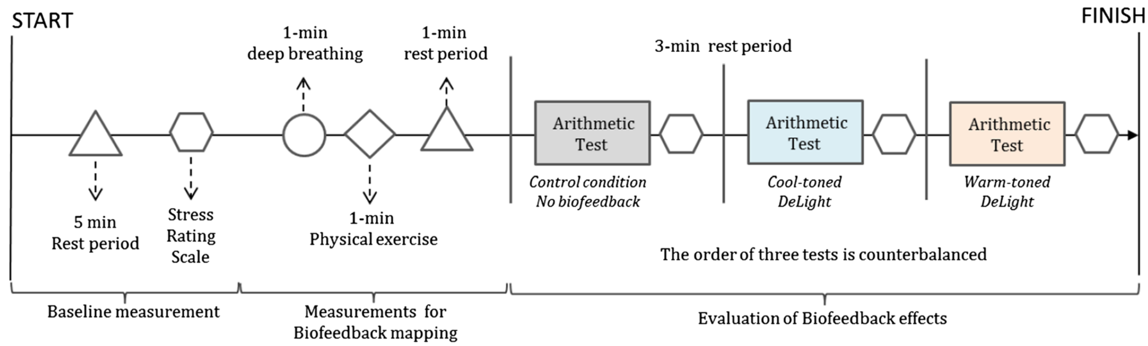

Fig. 4 Procedure of the experiment in study one

4.4 Results

The Shapiro-Wilk test indicated the physiological data (average HR and SDNN), and stress rating scales data were all normally distributed. A paired samples *t* test was conducted to compare the results to the baseline and between the three conditions. As the ratings on the questionnaire about lighting display were not normally distributed, a Wilcoxon test was conducted to compare the participants' opinions on the warm-toned light and cool-toned light displays.

4.4.1 Physiological data

Figure 5a shows the percent changes in the average HR and SDNN for each of the three conditions compared to the baseline. The average HR increased moderately due to the arithmetic test under all conditions. Especially in the control condition, the increase of HR ($M = 9.1\%$, $SD = 8.1\%$) was significantly higher than the baseline ($p = 0.039$). The increase of HR under the cool-toned ($M = 2.6\%$, $SD = 4.9\%$; $p = 0.027$) and warm-toned ($M = 2.6\%$, $SD = 4.9\%$; $p = 0.033$) lighting biofeedback conditions were significantly lower than the control condition. No significant differences were found between the cool-toned and warm-toned light conditions. These results suggest that the biofeedback through *DeLight* was useful in helping the users control their heart rate response to stress.

As the index of HRV, the SDNN is commonly expected to decrease under stress. This trend was also observed in our results. Compared to the resting baseline, the SDNN decreased significantly in the control condition ($M = -9.8\%$, $SD = 17.7\%$; $p = 0.04$) and cool-toned light condition as well ($M = -8.4\%$, $SD = 12.7\%$; $p = 0.02$). However, in warm-toned light condition, the SDNN did not decrease but had a small increase ($M = 1.8\%$, $SD = 20.2\%$). There was a significant difference in the SDNN for the warm-toned biofeedback and the control condition ($p = 0.04$). As mentioned above, the SDNN mainly indicate the biofeedback effects on self-regulation. When the participants noticed their increased stress through ambient light, they tended to manage stress by taking more deep breaths, which resulted in an enhanced HRV. The results indicate that the warm-toned light biofeedback was

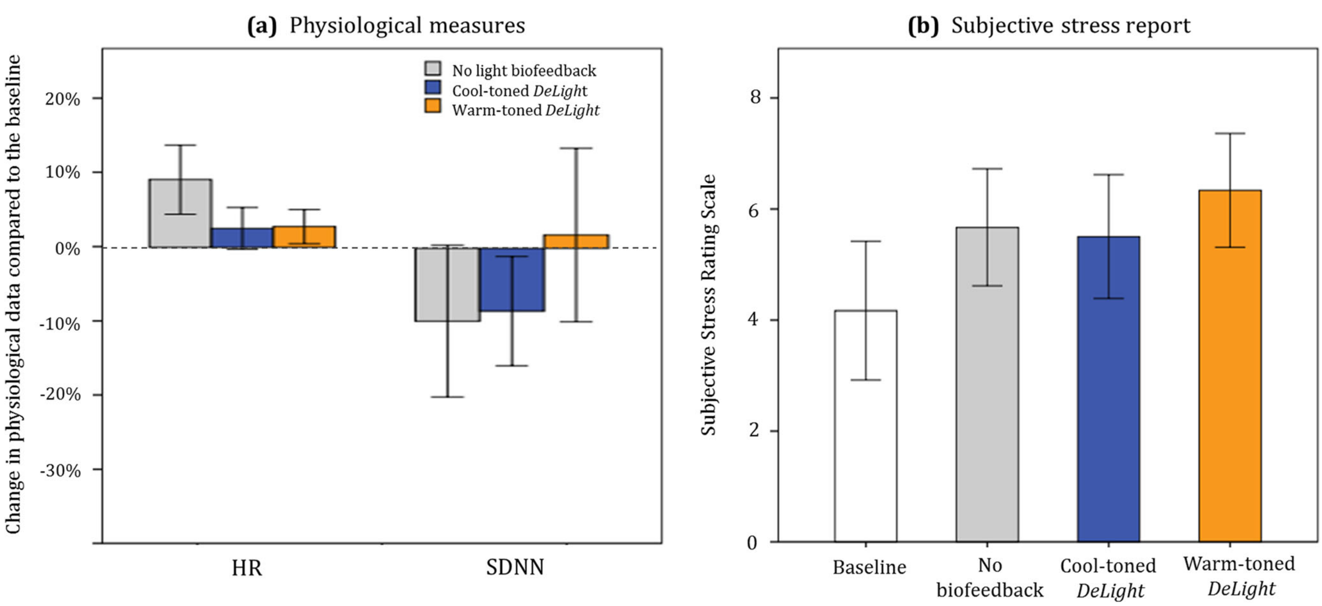

Fig. 5 Results of physiological measurements and subjective ratings on stress

more effective than cool-toned light in motivating the users in stress management.

4.4.2 Stress rating scale

From Fig. 5b, it can be seen that the participants' subjective ratings on stress feelings were increased in three conditions due to the difficult arithmetic problems. Interestingly, the participants under the warm-toned light condition reported the highest ratings on stress. The stress ratings were increased significantly in control condition ($M = 4.17$, $SD = 2.17$; $p = 0.01$) and warm-toned light condition ($M = 6.33$, $SD = 1.77$; $p = 0.02$) compared to the baseline. Under the cool-toned lighting condition, the increase was not significant statistically ($M = 5.5$, $SD = 1.9$; $p = 0.05$).

4.4.3 Questionnaire on lighting display

Figure 6 shows the results of the questionnaires about the lighting displays. The first question aims to investigate the salience of the lighting display. The ratings on the warm-toned light ($M = 6.0$, $SD = 2.6$) is moderately higher than cool-toned light ($M = 5.3$, $SD = 2.0$), but not significant. Regarding the second question about the association with stress, the rating on warm-toned light feedback was significantly higher than cool-toned light feedback ($M = 6.5$, $SD = 2.2$ vs. $M = 4.5$, $SD = 2.1$; $Z = -2.46$, $p = 0.014$). This indicates that most participants were more likely to associate a warm-toned light with their increased stress when it turned to orange. The third question is about relaxing experience. The ratings on the cool-toned lighting display were significantly higher than the warm-toned light ($M = 5.3$, $SD = 1.6$ vs. $M = 3.8$, $SD = 1.9$; $Z = -3.0.47$, $p < 0.05$), which suggests that a cool-toned light (e.g., green, cyan, or blue) may make users feel more calm and relaxed than a warm-toned light (especially an orange or red color).

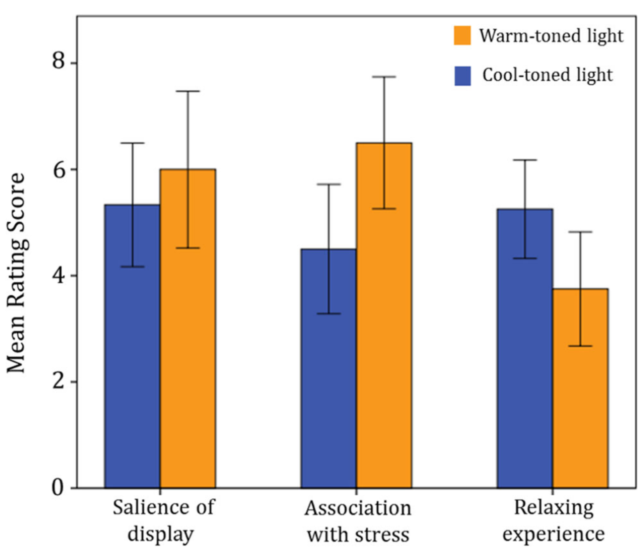

Fig. 6 Results of the questionnaires about the warm-toned and cool-toned lighting displays of *DeLight*

4.5 Summary of study one

We tested the feasibility of *DeLight* for stress intervention during a simulated stressful task. In this working mode, *DeLight* biofeedback system informs users about their stress level (increased HR and decreased HRV) by adjusting ambient lights from white to a more saturated color of warm-tone or cool-tone. We compared the effects of lighting biofeedback against the non-biofeedback condition, with two physiological measures (HR and SDNN) and subjective stress ratings as dependent variables. Overall, the results of physiological measures indicate that the biofeedback through ambient light can be a viable stress intervention during some high-stress tasks, improving individuals' awareness of stress, and further motivating them to take a "proactive" role in stress management.

The surveys of stress reports and lighting display reveal a strong psychological effect of colored light on user perception and experience. Warm-toned colors, especially orange or red, can be easily associated with a "warning sign," drawing more attention at the periphery. This makes them more efficient for stress indication. However, an orange-red-colored light may increase arousal or even tension regarding user experience. By contrast, a cool-toned lighting environment can bring more relaxation or calmness. Similar findings were also reported in [33–35].

In our design, the intensity of ambient light keeps unchanged to avoid affecting the regular work. We proposed to adjust the hue and the saturation of light to portray information. The hue value determines the color tone of a lighting environment, providing the basis for the user experience. For instance, a warm-toned light can be used to improve the arousal level of individuals for higher working efficiency. A cool-toned lighting environment can work to induce relaxation and calmness. The saturation can be modulated within a certain range to present information both at the periphery and the center of user's attention. We also found that the saturation changes in different color tone attract a different level of attention. A warm-toned color (e.g., orange or red) seems to move more easily from the periphery to the center of a user's attention. These insights were used in the light design of relaxation assistance mode for *DeLight*.

5 Study two: relaxation assistance with *DeLight*

Resonant breathing [50] is a common breathing technique for relaxation training. It can maximize the efficiency of pulmonary gas exchange and enhances the relaxing responses of the autonomic nervous system. Human heart rate can vary in

Table 2 Presentation mapping from biofeedback data to lighting parameters for the relaxation assistance mode

Biofeedback data	*DeLight* light display	Graphic display
Heart rate variability (HRV_{16})	Color of center and ambient lights	Background color of the displayed waveform and the application window
Inter-beat intervals (IBI)	Brightness interchange between center and ambient lights	Fluctuation of the waveform

synchrony with respiration (also known as respiratory sinus arrhythmia, RSA waveform), by which the IBI is shortened during inspiration and prolonged during expiration. When an individual performs a resonant breathing, his/her IBI data will show a sine-wave-like pattern, at which the heart rate variability achieves the maximum level. As such, RSA information serves as a "crutch" to assists the users in learning resonant breathing. An immediate feedback of IBI data (also known as IBI or RSA biofeedback) is often used as a tool for self-regulating physiological responses and practicing resonant breathing skills. The beneficial effects of IBI or RSA biofeedback training on stress reduction have been widely demonstrated, such as reducing performance anxiety for musicians [51] and occupational stress among industrial workers [52]. In the relaxation assistance mode, *DeLight* aims to facilitate resonant breathing during relaxation training. *DeLight* presents the IBI data by modifying the distribution of brightness among a set of lights and indicates the results of breathing regulation (improved HRV) by adjusting the color of the lights.

5.1 Biofeedback data processing and presentation mapping

In the relaxation assistance mode, the instantaneous IBI data is directly fed back to the users for assisting breathing regulation. The HRV data indicates the results of breathing regulation. As shown in Table 2, we calculate SDNN based on a shorter window of 16 intervals to increase the feedback sensitivity to breathing regulation. The HRV_{16} is calculated with the following formula: $HRV_{16} = ((15 \times HRV_{16} + |\mathrm{IBI} - IBI_{16}|)/16)$; $IBI_{16} = (15 \times IBI_{16} + \mathrm{IBI})/16$. The initial value of IBI_{16} is 600 ms.

As shown in Fig. 7, for relaxation assistance, the use of *DeLight* is different from the stress intervention mode that was the subject of the first study. The center light was held in the hands, close to the body of the users. One ambient lamp projected lights on the whiteboards in front of the user, and the other one was hung from the ceiling. The IBI data were represented through the brightness distribution of *DeLight*. We use IBI data to control the brightness of center and ambient lights in an opposite way so that the center light becomes bright during inhalation and the ambient lights become bright during exhalation. This mapping was designed based on 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 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 distance.

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 45,000 (cyan-blue), and the saturation value ranging from 0 to 250 was coupled to HRV_{16}. 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. 8, at the beginning of the relaxation training, the IBI data showed subtle variations. Therefore, 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.

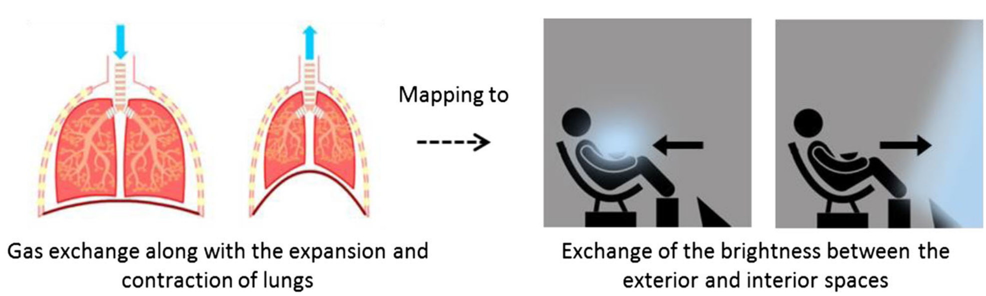

Fig. 7 The IBI data is presented by the brightness distribution of *DeLight*

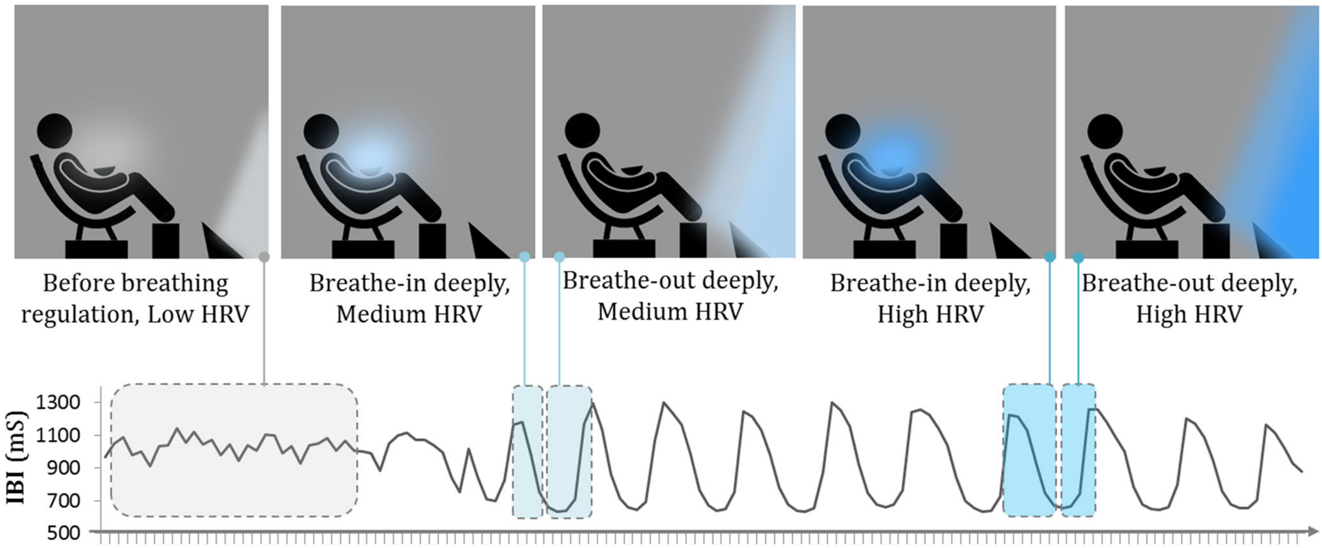

Fig. 8 The different lighting effects of *DeLight* adapted to the IBI and HRV data

5.2 Evaluation

The second study aimed to answer two research questions: (1) whether the lighting display of *DeLight* can be an effective alternative to a traditional graphic biofeedback for relaxation training and (2) whether the *DeLight* interface would offer users a more desired and relaxing user experience? Hence, we designed a within-subject experiment, in which all participants would complete two biofeedback-assisted relaxation sessions: one with *DeLight* display and the other one with the on-screen graphic display. We hypothesized that (1) the *DeLight* would be equally effective as the graphic interface regarding information display, but (2) would offer a more comfortable and enjoyable experience for relaxation. Figure 9a shows the setup of *DeLight* biofeedback system for relaxation training. As shown in Fig. 9b, 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.

5.2.1 Participants

Twenty 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.

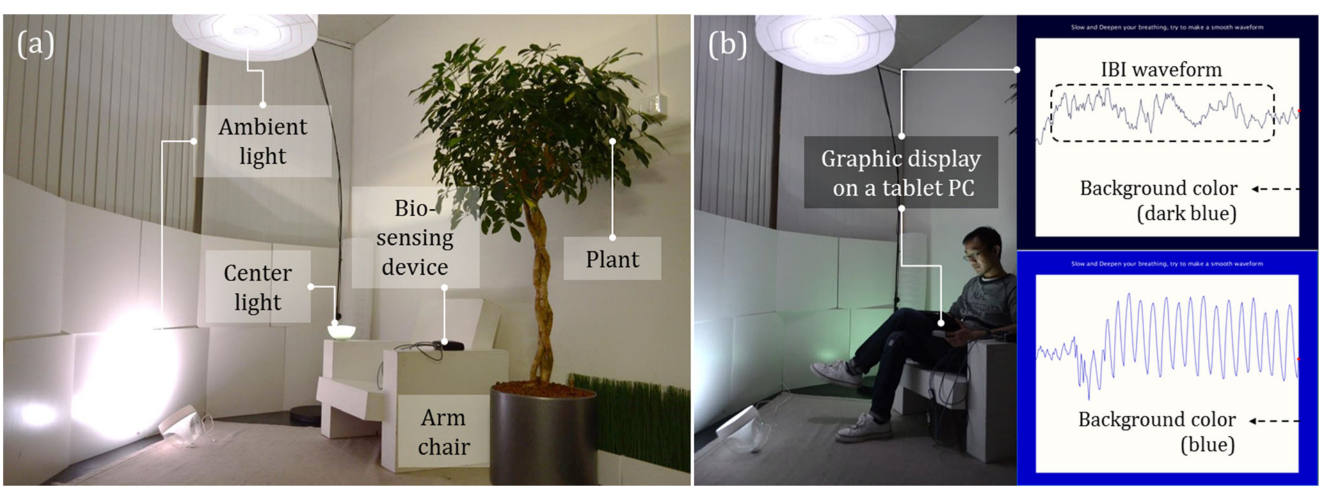

Fig. 9 **a** Setting up of the experiment in the Lab. **b** One participant watching the graphic display on the tablet

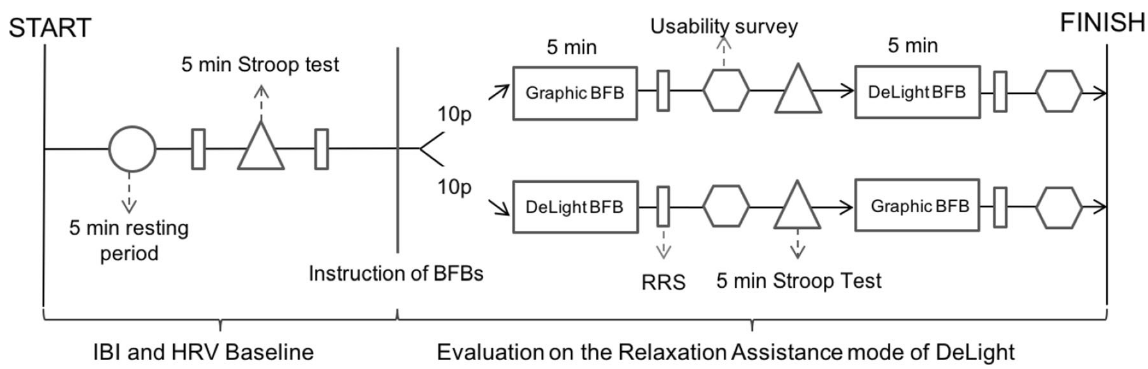

Fig. 10 Procedure of the experiment in the second study

5.2.2 Experiment procedure

The experiment followed the procedure shown in Fig. 10. 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 5 min, during which their physiological data and subjective relaxation ratings were measured as the baseline. After this resting period, participants completed a 5-min Stroop color-word test[7] for experiencing a simulated stress. The physiological data and subjective relaxation ratings were also collected. Next, the participant undertook two relaxation training sessions separately with biofeedback through graphic or lighting displays. Each relaxation session lasted 5 min. 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.

5.2.3 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."

5.2.4 Measurement and analysis

The independent variable was the biofeedback display, while the dependent variables consist of physiological measurements, subjective relaxation ratings, and the usability surveys. The physiological measures included heart rate (HR), heart rate variability (HRV), respiration rate (RSP-R), and skin conductance (SC). The physiological data were measured with the same bio-sensing device for biofeedback (*NeXus-10*, *Mind Media*) during the pre-test resting period, Stroop test, and two biofeedback sessions. The average HR and two HRV indices including RMSSD and LF% (percentage of low-frequency component) were calculated from the IBI data by the *Kubios* software. The HRV indices indicate the effects of biofeedback-assisted breathing regulation on the autonomic nervous system. In short-term recordings, HRV is highly related to the respiratory cycle of the participants [49]. When an individual performs well in deep breathing practice, in HRV power spectrum, the low-frequency components will increase significantly. Thereby, the LF% will be improved. In the time domain, the RMSSD will also be improved.

Respiration was measured with a respiration belt, producing a trace for abdomen movement. Respiration rate (RSP-R) (cycles per minute) was derived from the respiration trace. The skin conductance (SC) data was analyzed in the *Ledalab* software.[8] The continuous decomposition analysis (CDA) performs a decomposition of SC data into continuous

[7] Stroop color-word test: http://s3.mirror.co.uk/click-the-colour-and-not-the-word/index.html

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

signals of phasic and tonic activity. Because the tonic activities are highly subject-dependent and difficult to measure in the presence of phasic activities, we calculated the amount of skin conductance response (SCRs) as the index of arousal. It is proven that the SCRs carry information about the stress level of a person. It generally increases when an individual faces stress compared to non-stress situations.

We collected the participants' subjective relaxation feeling with a one-question relaxation rating scale (RRS). They completed the RRS after the pre-test resting period, the stress session, and two relaxation sessions immediately. To compare the usability and user experience of two biofeedback interfaces, we used the online *AttrakDiff* questionnaire[9] to collect the users' subjective rates on the hedonic and pragmatic qualities of the interface. The participants completed the questionnaire online after each biofeedback session.

5.3 Results

As shown in Fig. 11, by connecting and interacting with the *DeLight*, the participant's heart rate variations were dynamically coupled to the brightness and the color of light, creating an immersive lighting environment. As shown in Fig. 11a, before the biofeedback session, 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, 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 (see Fig. 11b, c). Along with the deep breathing in relaxation training, the IBI oscillation was enhanced. Figure 11d, e shows the lighting effects when the HRV is at a high level.

During the experiments, the IBI data was not detected for three participants due to the problem of cold hands and fingers. Further, 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 strong 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.

5.3.1 Physiological data

Heart rate A repeated measures ANOVA showed the average HR differed significantly between the sessions, $F(2.224, 35.585) = 8.626$, $p = 0.001$ (see Fig. 12a). Compared to the baseline, the HR increased during the stress session ($M = 1.83$, $SD = 4.07$). Surprisingly, the HR also increased in relaxation training with graphic biofeedback ($M = 2.97$, $SD = 4.55$) and the increase was even significant than the baseline. During the relaxation training with *DeLight* biofeedback, the HR was reduced ($M = -2.59$, $SD = 6.48$). Taken together, above results suggest that biofeedback through ambient lighting display did have an effect on the participants' heart rate after the stressful task. Specifically, 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 graphic biofeedback increased the participants' heart rate during the relaxation training.

Skin conductance responses A repeated measures ANOVA determined that SCRs differed significantly between baseline, stress, and two biofeedback relaxation sessions ($F(1.95, 35.18) = 18.77$, $p < 0.0005$). Figure 12b 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 ($M = 15.68$, $SD = 10.78$, $t(18) = -7.5$, $p < 0.0005$). 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, $t(18) = -3.52$, $p = 0.002$. 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 ($t(18) = -0.32$, $p = 0.756$). From this data, we can see that ambient lighting biofeedback resulted in the lower arousal level during the relaxation training.

Respiration rate A repeated measures ANOVA determined that respiration rate differed significantly between the baseline, stress session, and two biofeedback sessions ($F(1.63, 26.14) = 56.16$, $p < 0.0005$). Figure 13a 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 ($M = 15.86$, $SD = 4.27$, $t(16) = -4.44$, $p < 0.0005$). In contrast, compared to the baseline, the RSP-R decreased significantly during both graphic biofeedback ($M = 7.77$, $SD = 2.88$, $t(16) = 5.8$, $p < 0.0005$) and *DeLight* biofeedback session ($M = 6.78$, $SD = 1.98$, $t(16) = 7.8$, $p < 0.0005$). 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

[9] AttrakDiff Questionnaire, http://www.attrakdiff.de/index-en.html.

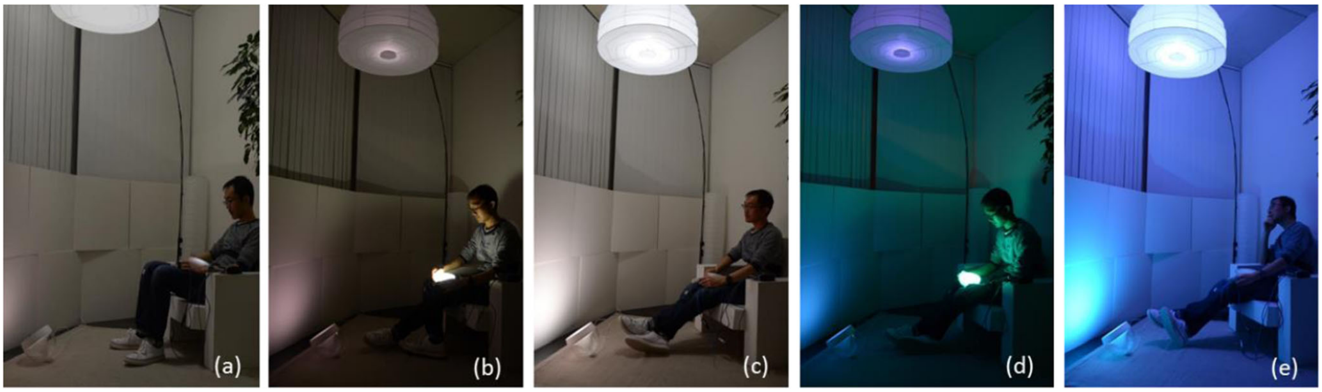

Fig. 11 **a**–**e** Light transitioning between the center light (**b**) and the ambient light(**c**) responding to the breathing regulation and from white (**c**) to blue (**e**) indicating an improved HRV in the *DeLight* biofeedback session

greatly promoted the breathing regulation during the relaxation training.

Heart rate variability Figure 13b, c shows the results of RMSSD and LF%. A *Friedman* test demonstrated a significant difference in RMSSD ($\chi^2(3) = 9.07$, $p = 0.028$) and in LF% ($\chi^2(3) = 21.96$, $p < 0.001$), between the sessions. A Wilcoxon nonparametric test demonstrated the RMSSD was significantly higher in graphic biofeedback ($Z = -2.15$, $p = 0.031$) and *DeLight* biofeedback session ($Z = -2.343$, $p = 0.019$) compared to the baseline. Similarly, LF% was improved significantly in graphic biofeedback ($Z = -3.15$, $p = 0.002$) and *DeLight* biofeedback session ($Z = -3.34$, $p = 0.001$). 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.

Breathing pattern The observation of the breathing pattern is interesting for understanding how the participants used the feedback information to regulate their breathing. Figure 14 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. 14a, 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. 14b) and even not needed for some participants (see Fig. 14c). 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. 14a, this phase of fatigue came earlier and tended to be more obvious compared to the *DeLight* sessions, e.g., Fig. 14c.

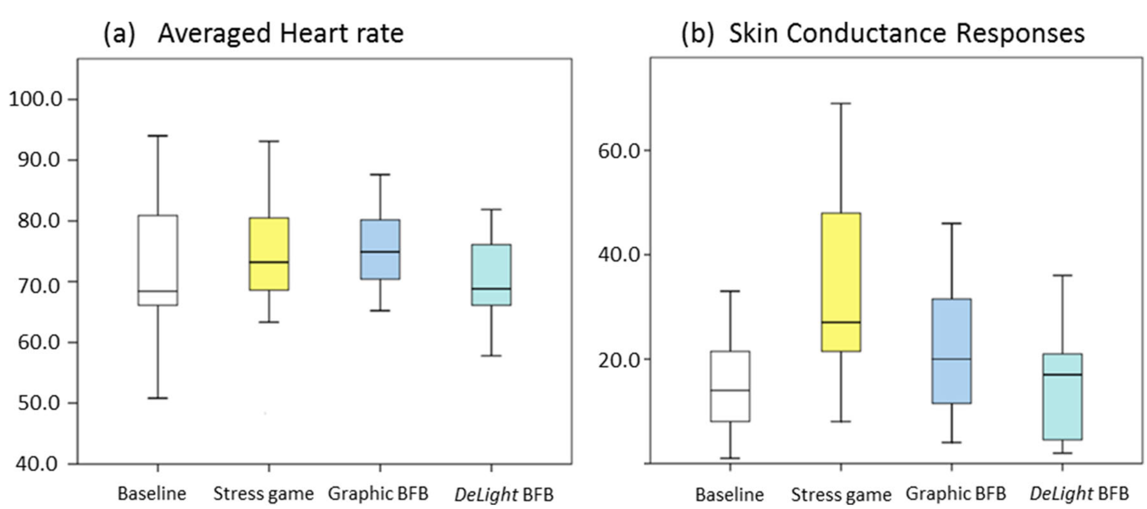

Fig. 12 **a** The results of averaged heart rate (HR). **b** The results of skin conductance responses (SCRs)

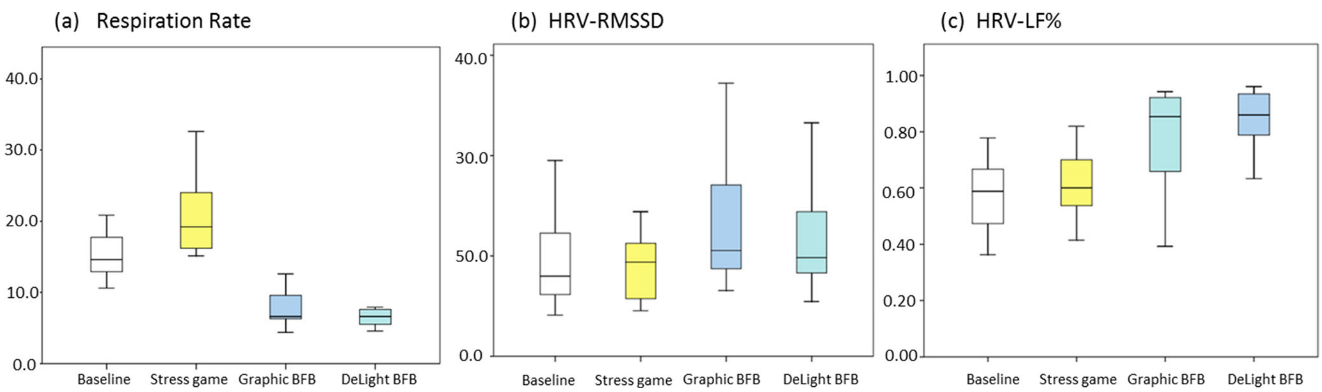

Fig. 13 **a** The results of respiration rate. **b** The results of HRV-RMSSD. **c** The results of HRV-LF%

5.3.2 Relaxation rating scale

Figure 15a 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 ($\chi^2(3) = 43.03$, $p < 0.005$). 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 ($M = 6.85$, $SD = 1.27$, $Z = -3.75$, $p < 0.001$). The RRS after the relaxation session with graphic biofeedback ($M = 5.16$, $SD = 1.83$) were improved significantly compared to the stress session ($Z = -2.35$, $p = 0.019$), but still significantly lower than the baseline ($Z = -2.98$, $p = 0.003$). The RRS after relaxation session with the *DeLight* biofeedback ($M = 7.53$, $SD = 1.17$) were significantly higher than the stress session ($Z = -3.74$, $p < 0.001$), the graphic biofeedback session ($Z = -3.75$, $p < 0.001$), and the baseline as well ($Z = -2.54$, $p = 0.011$). These results suggest that biofeedback through ambient light might have led to more mental relaxation than GUI display.

5.3.3 Usability survey

The *AttrakDiff* questionnaire was used for measuring the quality of usability and user experience of the graphic and *DeLight* lighting biofeedback interfaces. Figure 15b shows the overall results from the *AttrakDiff* system's report. The difference in pragmatic and hedonic quality between *DeLight* and graphic interface is significant. Regarding the pragmatic quality (PQ), which describes the usability/functionality of the interface/product, the *DeLight* was rated significantly higher than the graphic interface. The hedonic quality (HQ) dimension indicates to what extent the design can support those needs regarding the novel, interesting, and stimulating interaction and presentation styles. The *DeLight* also showed a higher HQ

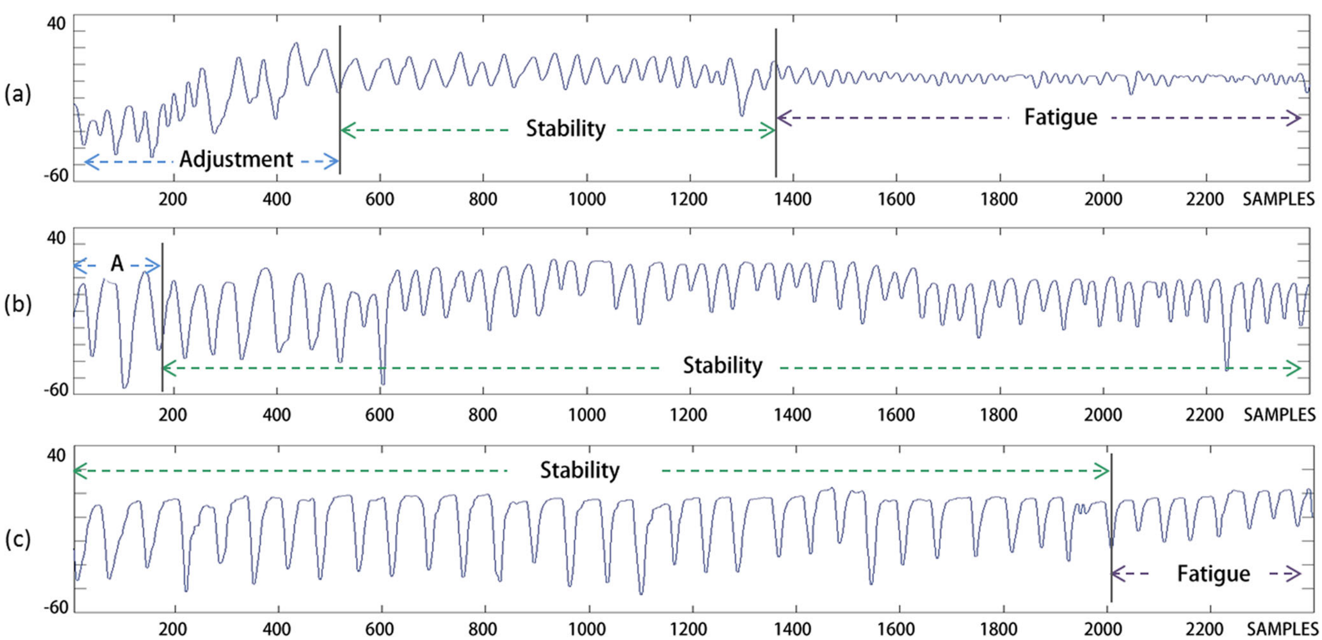

Fig. 14 Typical breathing trace from the two participants. **a** Respiration of S4 with graphic biofeedback. **b** Respiration of S4 with *DeLight*. **c** Respiration of S13 with *DeLight*

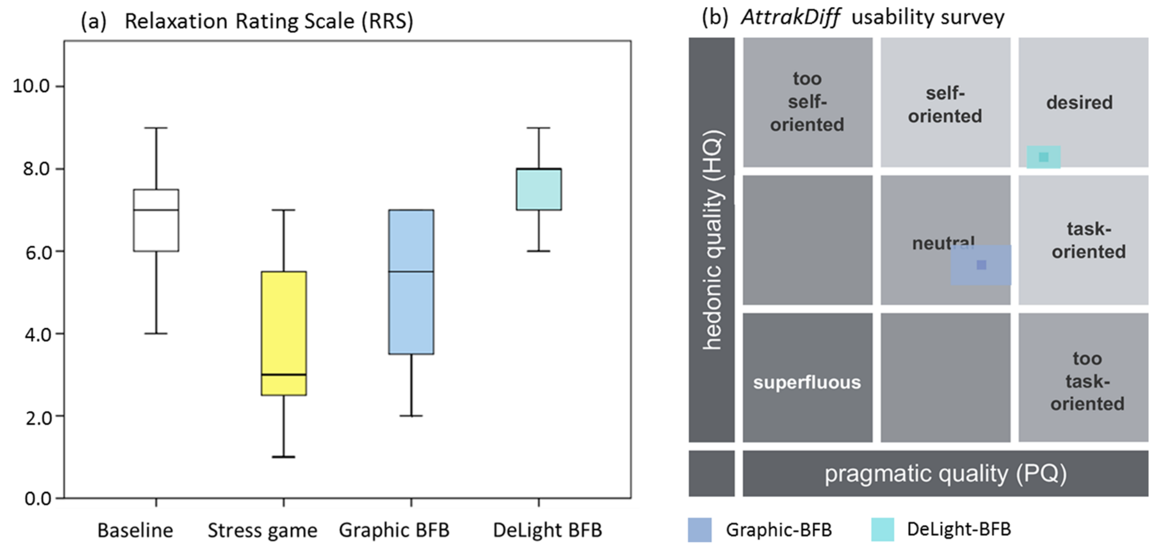

Fig. 15 **a** The results of relaxation rating scale (RRS) after each condition. **b** Result report of *AttrakDiff* usability survey

score than the graphic interface. The confidence rectangles for both hedonic and pragmatic quality of *DeLight* are smaller than for graphic interface, which indicates the participants were more agreed in their answers.

5.4 Summary of study two

In this section, we have presented the design and the evaluation of the relaxation assistance mode of *DeLight*. In this mode, *DeLight* adapts the brightness distribution and color of the lights to represent the IBI and HRV data for guiding a slow and deep breathing pattern. We compared the lighting interface of *DeLight* against a traditional graphic interface, with the physiological measures, subjective relaxation ratings and usability questionnaires as dependent variables. The results of the HRV and respiration rate data are consistent with each other. Biofeedback through both graphic and *DeLight* interfaces led to a lower respiration rate and an increased HRV. These results support our first hypothesis that the *DeLight* can be an effective alternative to traditional GUI biofeedback for assisting breathing regulation during a relaxation training.

Compared to the graphic biofeedback, *DeLight* biofeedback led to a lower heart rate and SCRs, which support our second hypothesis that *DeLight* interface would offer users a more relaxing user experience. The results from relaxation rating scale also indicate that *DeLight* biofeedback led to a greater mental relaxation. The improvement in subjective RRS and the decrease in heart rate and SCRs, as shown in Figs. 12a, b and 15a, respectively, are consistent with each other. Finally, in terms of usability and user experience, the *DeLight* biofeedback was preferred over the graphic biofeedback. This suggests that the lighting biofeedback system might be a desired tool for assistance in relaxation training.

6 Discussion

In this paper, we have presented *DeLight*, a biofeedback lighting environment that could not only inform users about their stress level at the periphery of attention through the subtle changes of light color but also assist users in a relaxation training by presenting respiration-related IBI information through the dynamic changes of brightness distribution and color. In summary, the findings confirm the hypotheses that (1) the biofeedback through subtle changes of ambient light could support stress intervention, improving self-awareness of stress and further triggering a behavioral conditioning, such as deep breathing, and that (2) the biofeedback through the dynamic changes of lights could assist relaxation training, not only promoting physiological regulation (lower breathing rate and higher HRV) as effectively as the traditionally graphic biofeedback but also enhancing physical and mental relaxation (lower SCRs and HR, higher subjective relaxation ratings). Based on these results, we see there are three potentials for *DeLight*.

Firstly, *DeLight* is a good use case for calm information display. The *DeLight* system can be seamlessly embedded into a physiologically responsive home or work environment, where ambient light is used to communicate information without taking users out of their primary tasks. As suggested by Weiser in [2], "a calm technology should move easily from the periphery of our attention to the center, and back." For instance, the inhabitants can be aware of their stress through general feelings toward the "color temperature" of light. A cool-toned light environment has a positive effect on "stress lowering," and the saturation changes in a cool tone occupy only a small amount of attention. By contrast, when the light color changes in a warm tone, it tends to move into the center of attention, working as a "warning sign" for stress intervention. In the context of everyday stress management, we argue that biofeedback technology should both *encalm* and *inform*. To achieve this, we suggest that light can turn into a cool-toned color, using its relaxation effects to mediate the increased stress within a healthy range. However, when the stress continues and becomes harmful, the light can turn to a warm-tone color, informing the users and initiating stress management.

Secondly, *DeLight* performs as *Persuasive Technology* [53] in the domain of health management. Lighting, as an ambient persuasive medium, has been used to trigger the behavioral changes, such as taking the stairs instead of the elevator [54] and doing more physical activities in the workplace [29]. As suggested by [26], the inhabitants tend to show some behavioral and physiological responses to an adaptive lighting environment that incorporated elements of biofeedback. In the first study, most participants showed increased stress responses due to the difficult arithmetic problems. When the increased HR drove the ambient light turning orange or even red, the participants were motivated to take more deep breathing, which helps to maintain an autonomic balance. We suggest that a biofeedback-driven adaptive lighting environment can be used as a persuasive technology promoting healthy behavior, e.g., taking more deep breathing at work.

Thirdly, *DeLight* can enhance and augment a relaxation experience with biofeedback technology. The user experience during a biofeedback-assisted relaxation training can play a significant role in the effects of relaxation mentally and physically. The external signal from the user interface might be a stimulus inducing relaxation or causing a new anxiety adversely. For some individuals, the traditional graphic displays can initiate or exacerbate anxiety during a relaxation training [55]. In study two, this "relaxation-induced anxiety" has also been observed in some participants during the graphic biofeedback session. More than half participants (9/17) showed a somewhat unexpected increase (not statistically significant) in the averaged heart rates during the graphic biofeedback session compared to the stress session. Four participants showed increased skin conductance responses with the graphic biofeedback. Nearly half of the participants (9/20) reported less or same relaxation ratings on the graphic biofeedback compared to the stress session. In contrast, in *DeLight* biofeedback session, this "relaxation-induced anxiety" seemed to occur rarely. Only two participants showed an increased HR, and one participant showed the increased SCRs with the lighting biofeedback.

In clinical settings, most biofeedback systems applied in stress alleviation and relaxation training still rely on-screen-based graphic or numeric displays. Recently, many efforts from HCI realm has been made to explore new forms of biofeedback, such as musical displays [23, 25], shape-changing displays [56], games [20], VR displays [57], or responsive architectures [26]. Compared to a VR-based or architecture-based immersive relaxation training system, *DeLight* offers a lightweight solution to strike a balance between an immersive experience and ease of deployment. We see the potential of *DeLight* to be embedded in the home or office settings leveraging a wide range of smart LED light bulbs (e.g., *Philips Hue*, *LIFX Gen 3*,[10] *GE C-Life*,[11] or *Ikea Tradfri*[12]). *DeLight* system may color the home, office, or a lounge room of a hospital, turning it into an ad-hoc biofeedback space which encourages self-regulation and enhances relaxation. For instance, with the proposed *DeLight* system, a user can be aware of his/her increased stress through the light of turning warm in the office, and manage the stress by taking a few deep breaths to restore the lights. The user can also perform a relaxation training at home, where the lights change smoothly responding to her breathing. In this scenario, ambient light is not only an alternative information carrier but also a booster for relaxation. The combination of informative and relaxing aspects makes the lighting interface both helpful and pleasant for the user.

There are some limitations in this work. This work mainly focused on the design of the lighting interface, whereas bio-sensing technologies have not been explored. To ensure the accuracy of measurements, we used professional bio-sensors according to the state of the art. In the experiments, the photoplethysmogram (PPG) sensor was fixed on the earlobe (study one) or fingertip (study two) with the clip to measure the blood volume pulse for calculating IBI and HRV. The requirement on the attachment of the bio-sensor somewhat limited the evaluations of DeLight in a laboratory setting. Thereby, further investigation and exploration into new contactless or more unobtrusive sensors are strongly recommended. For instance, the user's breathing and heart rate can be monitored by using a low power wireless signal without body contact [58]. The IBI and HRV data can be measured with wearable devices (e.g., a watch [59], an earphone [60] or a pair of glasses [61]). In office scenarios, heart rate could also be estimated from computer webcams [62] or detected by the sensors integrated into advanced office furniture, e.g., an office seat [63].

The studies show the effect of an ambient light system on a control-work scenario. Although the laboratory was set up for simulating a (home) office scenario, the short-term lab-based evaluation might not be adequate to reveal the advantages and disadvantages of biofeedback lighting environment in long-term everyday use. In various environments, the proposed system might meet new challenges. For instance, the current *DeLight* system may not suit for a public workplace shared by a group of users. The setup of *DeLight* in a different home

[10] *LIFX Gen 3*, https://eu.lifx.com/collections/featured-products#lights.

[11] *GE C-Life*, https://www.cbyge.com/products/c-life.

[12] *Ikea Tradfri*:https://www.cnet.com/products/ikea-tradfri-smart-lighting-kit/review/.

layout might have an adverse effect. In the future work, we suggest first to refine the *DeLight* system by updating the bio-sensing approach and second to design a long-term field study with a larger number of participants. It would also be interesting to improve the *DeLight* system for multiple users. Finally, it may be worthwhile to further investigate the user feelings and experience of the *DeLight* system in everyday use. A self-report measure like *AttrakDiff* that was used in the current study generally focuses on the usability of the interactive system. User interviews in field evaluations can give more qualitative data about user experience and also allow for better observing the users' behaviors, such as when and how they use *DeLight* in stress management.

7 Conclusion

This paper presents the design of *DeLight*, a light-based ambient biofeedback system for stress management. *DeLight* works in two different modes for both peripheral stress intervention and immersive relaxation training. Two user studies were conducted to investigate each mode regarding (1) the feasibility of ambient light for biofeedback display and (2) the effect of a colored lighting environment on relaxation. The first study has shown that the color-modulated lighting biofeedback can be a viable stress intervention by creating ambient awareness of stress with a cool-toned light (in the periphery of attention) and further motivating self-management of stress with a "warm-toned" light (at the center). The second study has shown that the proposed lighting interface can be an alternative to traditional GUI biofeedback for assisting breathing regulation during a relaxation training. Also, the relaxation training with biofeedback provided in a cool-toned lighting environment led to a greater physical and mental relaxation.

The contribution of the paper is twofold: First, this work revealed the effects of different colored light on human's awareness of light changes, psychological feelings, and physiological responses. Regarding the ambient awareness, the saturation changes in different tones occupy different amount of attention: cool-toned changes tend to be at the periphery, and warm-toned changes move easily into the center of attention. Regarding psychological feelings, an orange-red-colored light has a strong "warning" effect that can be used as a *Persuasive Technology* to trigger behavioral changes. Regarding physiological responses, a warm-toned light can increase arousal while a cool-toned lighting environment can bring more relaxation or calmness. Second, regarding the practical implications, the design of *DeLight* stands out as a promising combination of biofeedback, ambient lighting display and an application to stress management and relaxation assistance. The studies validated the feasibility of ambient light for biofeedback display and revealed its advantages for calm information display and relaxation assistance. We see our work as a proof of concept, an instantiation of the model of *Ubiquitous Biofeedback* proposed in [20]. This work strengthens the idea of transforming the biofeedback paradigm from the desktop GUIs to the ambient interfaces that blend into everyday living.

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