

Breathe with the Ocean: a System for Relaxation using Audio, Haptic and Visual Stimuli

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Abstract

In this paper we present the “*Breathe with the Ocean*” system concept, which is a breathing guidance system that aims to help a user relax. It provides an immersive experience where the user is virtually present at an ocean shore. We describe the design and implementation of three embodiments of this concept and preliminary evaluations based on trial sessions. The feedback provided by the three systems to the user is in the form of audio, haptic (tactile) and visual (light) stimuli. Haptic stimuli are provided through a novel actuation device that we developed, the Touch Blanket. The three systems introduced are respectively a fixed-rate breathing guidance system, an adaptive breathing following system and an adaptive-rate breathing guidance system that maximizes heart-rate variability amplitude. We discuss the advantages and disadvantages of using open-loop versus closed-loop implementations of these types of systems, as well as our experiences so far in using multimodal stimuli for breathing guidance.

1 Introduction

Over the past decades numerous studies have been undertaken to determine the factors that cause relaxation at a psycho-physiologic level and the best methods to induce it. At the same time, a plethora of relaxation products (e.g. [1] [2] [3]) appeared on the market: some of these substantiated by scientific studies, others simply implementing one’s idea of what might “feel good”. We believe that in building a successful system for relaxation, one has to carefully choose the *stimuli* to be rendered, and the *policy* of rendering the stimuli.

Regarding the stimuli, several studies [4] have highlighted the potential positive effects of haptic (tactile) stimulation on the human body, emotions, mood, and health. Nevertheless tactile stimuli are not the only stimuli helpful for inducing relaxation. An interesting question is whether additional stimuli (i.e. sound or light) synchronized with haptic stimuli can emphasize their effect. A related question is whether a combined stimulation can induce relaxation more effectively than a single type of stimuli can do.

Other relevant questions are related to the activation time(s), intensity and duration of the stimulation itself for the purpose of relaxation. For example, should the stimuli be applied according to a predefined, fixed policy? Or should the stimulation be adaptive, responding to the current state and the personal needs of the user? And, in both cases, what should be the *policy* that determines the application of stimuli, in terms of modalities used, activation time(s), intensity and duration?

In this paper we aim to present and compare a number of system embodiments of our concept “*Breathe with the Ocean*”, created for the purpose of relaxing a user. We explore three different system implementations, describing their advantages and disadvantages that were revealed during initial trials. The systems we present all implement a form of breathing guidance, a known technique to help people to relax [5] [6]. Breathing guidance means indicating to a user, during a session, in some way how the user should breathe in order to obtain beneficial effects for health or increase feelings of well-being. In our systems, breathing guidance is offered to the user by means of haptic, audio and light stimuli.

The main reason why we investigate a multi-sensory form of breathing guidance is our working hypothesis that involving more of the senses in a relaxation experience will increase both enjoyability and effectiveness of a relaxation session. For example, one aspect is that a guiding stimulus could be easier to follow if it is simultaneously presented through two or more modalities.

We organize our presentation as follows. Section 2 first presents the “*Breathe with the Ocean*” concept briefly, followed by a review of related work in Section 3 which also is intended to justify our

choice of stimuli and choice for the technique of guided breathing. Section 4 presents the design and implementation of three embodiments of this concept, including the technologies employed and the chosen policies for rendering the stimuli. Section 5 describes our initial evaluation of the three embodiments, including our experiences so far in using multimodal stimuli for breathing guidance, followed by the conclusions section.

2 Concept

The “Breathe with the Ocean” concept entails a system that induces relaxation by providing a multi-sensory experience, where a user is virtually present at the shore of an ocean where he/she can hear and feel the waves of the ocean “washing” over the body. The concept does not rely heavily on visual stimuli and therefore it allows a user to close the eyes at any time, which may further help to increase relaxation.

We used the analogy with the ocean due to its natural association for most people with a relaxing setting, and because we identified the opportunity to integrate breathing guidance into the ocean setting of rhythmic ocean waves. Breathing guidance can have an additional relaxing effect. At the same time we recognize that this is not the only analogy we could have implemented, other settings from nature could be used as well, while the concept here represents one option out of many.

In our concept, the waves of the ocean are used to relax the user and to provide breathing guidance to the user, while the surrounding space is illuminated with a relaxing visual ambiance fitting the theme and purpose of the exercise. The visual ambiance is characterized by low-intensity, gentle tones of colored light. All three systems we present in this paper implement an imitation of ocean waves by combining

1. a "haptic wave" moving up and down the body, rendered using a matrix of vibration motors
2. ocean wave sounds rendered to audio headphones (or audio speakers) in synchrony with the haptic actuation.

In addition to the ocean wave sounds, a background relaxation music track can optionally also be played intermixed with the wave sounds.

The breathing guidance is linked to the haptic stimuli in the following way: when the haptic effect moves up from the feet towards the shoulders of the user, an activity of breathing in is implied. When the haptic effect moves down from the shoulders towards the feet of the user, an activity of breathing out is implied.

3 Related Work

To achieve the specific haptic stimulation which we refer to as "haptic waves", we make use of the *Touch Blanket* (see Figure 2 or [7]), which is a haptic actuation device developed within Philips that can provide personalized haptic effects to one or two users and can provide subtle haptic motion patterns, targeting specific body parts. The technology is the same as used in the work of Lemmens et al. [8].

Our rationale to use music is that various studies have shown that audio stimuli, in particular music can have a positive effect on relaxation. For example in [9] the authors show the influence of music on the level of nitric oxide and how this molecule is to a large degree responsible for physiological and psychological relaxing effects of listening to music. In [10] the authors show that although there are wide variations in individual preferences, music seems to directly affect the autonomic nervous system and as a consequence has further effects at a physiological level. Their tests have shown that music reduces anxiety and improves mood for patients in various situations such as while in intensive care units, while undergoing procedures or while receiving palliative care. In [11] the authors studied a “music enhanced therapy” which combines music and tactile stimulation embedded in a recliner, with traditional counseling techniques. The therapy was found to benefit musicians in that it reportedly reduced anxiety, improved mood, and reduced performance anxiety.

There is also evidence that haptics in the form of vibrations can induce relaxation. Wigram [12] reports an experiment with vibro-acoustics used on 60 healthy subjects (30 male, 30 female). Three conditions were evaluated: music + vibrations, music only, and the control condition (no stimulation).

The UWIST-MACL (MACL = Mood adjective check list) was used before and after the session to measure self-reported mood, and blood pressure and heart rate were measured. The self-reports show a significant decrease of *arousal* scores for the music + vibrations condition, compared to music alone or to the control group. In turn, the music-only condition shows a smaller but still significant decrease in arousal compared to the control condition. For blood pressure and heart rate, no significant results were found except that heart rate for participants in the two groups *music* and *music + vibration* combined was significantly lower than for participants in the control group.

Our work also builds on research conducted on the topic of guided breathing. Guided breathing exercises are linked to beneficial physiological effects related to relaxation such as decreased respiration rate (RSP rate) and increased Heart Rate Variability (HRV) amplitude. The connection between RSP rate and HRV amplitude, namely that guiding a user's breathing to progressively lower RSP rate leads to higher levels of HRV amplitude is documented in a number of literature studies [13] [14] [15] [16].

Many breathing guides available are quite straightforward, simply guiding the user at a fixed six respiration cycles per minute (c/min) according to a scientific finding [13] that around this rate *on an average person* the HRV amplitude is increased to a maximum. On the market, more notable products that offer breathing guidance for the purpose of relaxation are *emWave* developed by *HeartMath* [17] and *RESPeRATE* [18] developed by *Intercure*. Both products use a single sensor (respectively one for HRV and one for respiration) to adapt the breathing guidance rate based on the current state of the user.

Similar to *emWave* and *RESPeRATE* we also make use of HRV amplitude sensing and respiration sensing. The difference with existing systems is however that our breathing guide allows multimodal (haptic, audio and visual) stimulation, providing a whole experience aimed at inducing relaxation. The user in our case lies down on the Touch Blanket while hearing music and the sound of waves, while being surrounded by a visually relaxing ambiance. In contrast *emWave* is a small portable device which provides functional audio feedback and functional visual feedback by means of colored LEDs. *RESPeRATE* provides music feedback to guide respiration plus very simple indications in a LCD display. It is implemented as a portable device as well.

In comparison, the adaptive systems that will be presented by us in sections 4.3 and 4.4 provide multi-sensory stimulation and feedback, including tactile stimulation. Additionally the system described in section 4.3 takes a different approach than existing guides, by *following* (rather than just guiding) the natural breathing pattern of the user, while still inducing the user to progressively lower his/her respiration rate. In this case the system gives a form of bio-feedback, which allows the user to see/hear/feel whether their respiration lowers in rate and whether respiration is regular.

4 Design and Implementation

In this section we describe the design and implementation of three systems embodying the “Breathe with the Ocean” concept. Each system can be classified as either open-loop or closed-loop. We first describe the characteristics of each of these classes. Thereafter we describe the design and architecture of one open-loop and two closed-loop systems that all provide haptic, audio and visual feedback to the user.

4.1 Open-loop versus closed-loop

Open-loop systems execute according to a predefined strategy, and do not change their execution based on input(s) related to the state of the user. In other words, open loop systems are non-adaptive, usually a “one size fits all” type of system. In contrast, closed-loop systems are systems that adapt their execution according to input related to the state of the user. In particular, the closed-loop system in Section 4.3 includes the following components that make it closed-loop:

1. A measuring component which determines the current levels of different bio-signals or bio-signal features such as respiration rate, heart rate, or HRV amplitude;
2. An actuation component that renders the guided respiration rate by means of audio, haptic and/or visual feedback. The guided rate is based on the measurements.

In addition, the closed-loop system in Section 4.4 includes:

3. A component that interprets/assesses the relaxation state of the user, based on the measured and analyzed bio-signals;
4. A component that determines the user's personal and optimal respiration rate based on the data obtained by the previous component.

4.2 Embodiment 1 – fixed rate, open-loop breathing guide

The first embodiment of the “Breathe with the Ocean” concept that we built was an open-loop system. The usage scenario of this system is that while the user lies down on the Touch Blanket (see Figure 2), a haptic effect is rendered starting from the feet of the user towards the head of the user, and then back again. This cycle then repeats for the duration of the session. As mentioned before, these "haptic waves" are synchronized with audio samples of approaching and retreating ocean waves on a shoreline.

The intention of this system is that both the audio signal and the tactile stimulation provide breathing guidance to the user. Therefore, the audio/haptic waves occur at a frequency appropriate for a relaxed breathing pace. According to literature [13], a typical respiration rate at which human beings achieve maximum values in HRV amplitude – which is associated with relaxation – is at 6 breathing cycles per minute (c/min). Therefore, in this implementation the waves are rendered at the fixed, predefined rate of 6 c/min. A straightforward addition for this system could be a knob or slider to let the user easily adjust this rate.

The visual stimulus is provided by four Philips *LivingColors* [19] lamps set on a yellow/orange color intended to imitate the colors of sand and sun. Other color options such as blue to imitate the color of the sky or the ocean are possible as well - the current color is just one of many alternatives that we chose based on our own preference. The light intensity and color are fixed during the relaxation session.

The Touch Blanket exterior and interior are shown in Figure 2. On the outside, it looks like a conventional blanket and it can be conveniently spread on top of a seat or sofa. Inside, it contains 176 small, individually controllable small vibration motors (~1cm diameter), arranged in a 2D matrix. Each motor can be set to 25 different intensity levels with an update period of less than 50 milliseconds. The frequency and intensity of the motors are not separately controllable, because for this type of vibration motor higher intensity is directly linked to higher rotation speed and hence to a higher vibration frequency. Figure 3 shows how a single user can lie on the blanket, with (optionally) the top half of the blanket on top of his/her body to have haptic stimulation all around the body. Figure 4 shows a simplified system architecture diagram of the entire system.



Figure 1: Touch Blanket spread over a sofa. The blanket consists of two separate halves, one for the back area and one for the seat area.

To control the Touch Blanket, a C++ PC application was developed that generates tactile effects synchronized to the audio of approaching and retreating waves. This application uses effect scripts specifying what tactile effects are to be played when. In our experience so far and through user feedback we received, we learnt that what constitutes a good tactile experience, is a matter of personal taste. Especially, different intensities of haptic effects were preferred by different people. Therefore, in general a suitable UI to allow personalization of haptic effects is valuable to have. In our current system, only a basic slider control is available for users to adjust the intensity of effects between levels 0-25.



Figure 2: View inside the Touch Blanket, showing the wiring and part of the matrix of vibration motors. The motors are attached to the fabric with white adhesive tape.

Respiration sensor Haptic 'wave' up:
breathe in

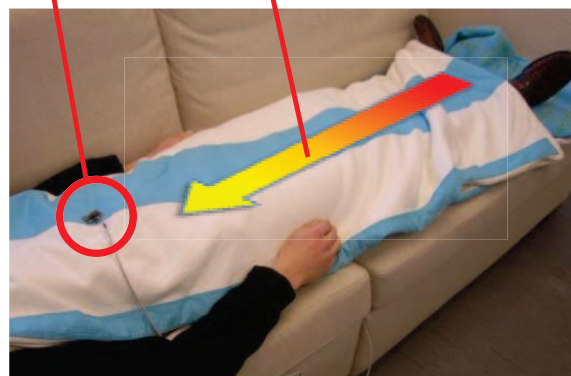


Figure 3: User lying on a sofa wrapped in the Touch Blanket, covering both back and front of the body. This provides haptic effects on both sides of the body. The respiration sensor (accelerometer) used in system embodiment 2 is placed at the abdomen. The arrow indicates a "haptic wave" effect travelling from the feet to the shoulders.

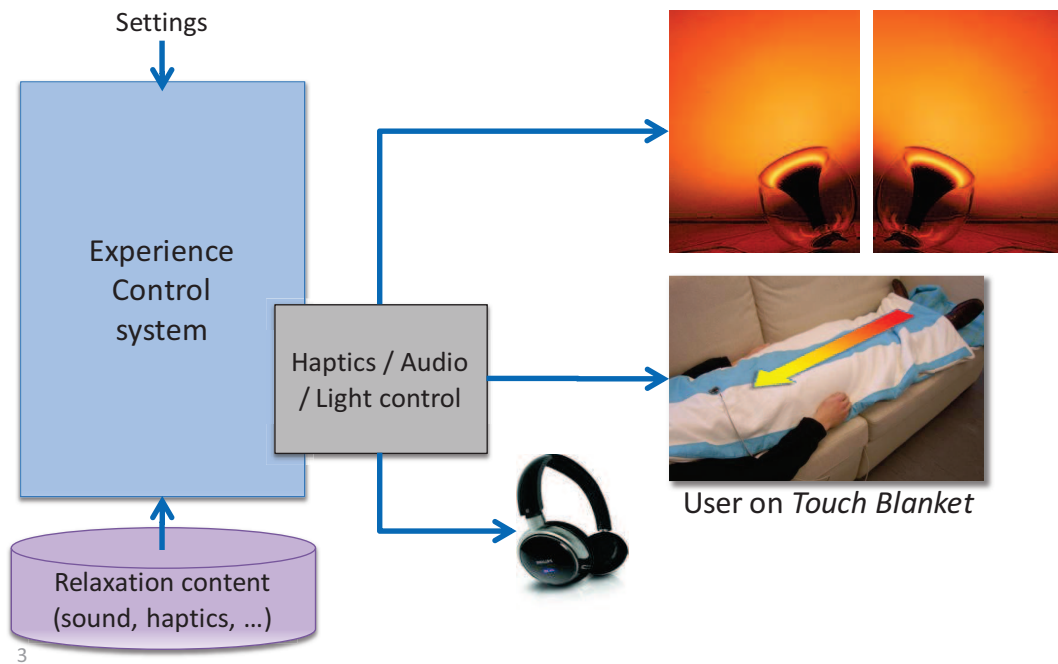


Figure 4: Simplified system diagram of embodiment 1, open-loop audio-haptic breathing guide

4.3 Embodiment 2 - Following the user's respiration pattern

Similar to the open-loop system described above, also in this embodiment the user lies down on the Touch Blanket, while haptic waves are rendered from the feet to the head of the user and vice-versa. Also here, the haptic waves are synchronized with audio content. Figure 5 shows a simplified system architecture diagram of the system.

In contrast to the previously described system, this implementation is a closed-loop system. It adjusts the stimulation based on the user's current respiration rate and inhale/exhale pattern. Specifically, the haptic, audio and light effects are adjusted to *follow* the user's respiration. In this case the user is not forced to follow a fixed rhythm provided by a guide but can freely choose a natural inhale/exhale breathing pattern.

The idea here is that the system should not guide directly, but rather provide through the multi-sensory stimuli a form of *bio-feedback* to help the user become aware of how they breathe: whether they succeed to slow down their breathing during the exercise and whether they breathe regularly as intended by the exercise. For example, a user who would breathe quickly or irregularly would also perceive quick and irregular audio, haptic and light stimuli which we believe would be typically perceived as annoying by a user (based on our experience from a previous, yet unpublished study). This may provide a motivation to the user to breathe slower and more regular, thereby receiving the "reward" of calm and predictable stimuli from the system.

The feedback is provided as follows: a haptic wave is rendered from feet to head whenever the user inhales, and from head to feet whenever the user exhales. The time duration of the haptic wave rendering in either direction is adjusted to fully match the inhale/exhale respiratory cycle. Given the fact that the audio content is synchronized with the haptic effects, it follows that the sound of ocean waves matches the user's respiration rate and pattern as well.

Another difference compared to the previous system, is that this implementation provides feedback in the form of light, whereas previously the light was used purely for ambiental purposes. The visual feedback we provide here is given by varying the light intensity of the *LivingColors* lamps while the user

performs the breathing exercise: the light intensity increases when the user inhales, and the intensity decreases when the user exhales.

As a result of the bio-feedback provided by the multimodal rendering we meant the user to be able to implicitly recognize the level of his/her performance while executing the breathing exercise. In response, the user should be learn over time to adjust his/her breathing accordingly. It is likely that spending more time on the breathing exercise will improve a user's skill in the technique. Once the user is able to breathe slowly and deeply with minimal effort, optimal relaxation may be achieved. The current implementation does not provide an explicit indication on the user's performance level, i.e. how close the respiration rate is to the optimal rate or how regular the breathing pattern is.

The LivingColors lamps that provide the light effect are wirelessly controlled using a proprietary RF protocol. This protocol allows a single controller to control the light intensity and color selection for one or more (up to four) lamps.

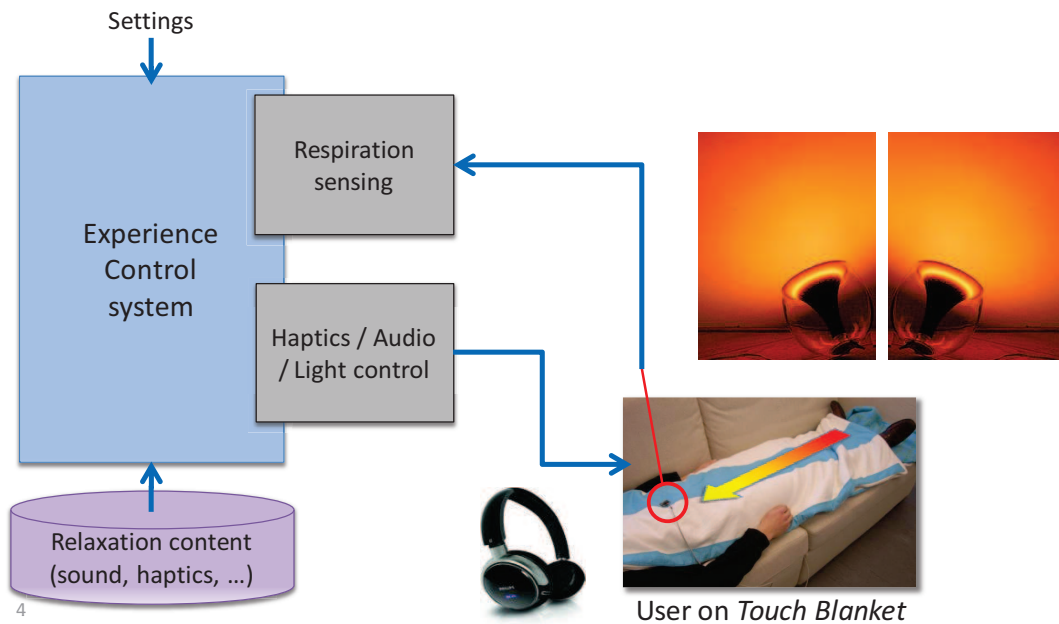


Figure 5: Simplified system architecture of closed-loop breathing following (bio-feedback) system

4.4 Embodiment 3 - adaptive breathing guide for maximizing heart-rate variability

Several publications ([13], [14], [15], [16]) show that guided breathing at steadily decreasing breathing guidance rates induces a lower respiration rate of the user and higher values of the HRV amplitude, which is linked to states of relaxation. This work also shows that for each user there exists a personal, optimal respiration rate which induces maximum HRV amplitude.

The disadvantage of fixed breathing guide systems (including our embodiment 1) is that these cannot maximize the HRV amplitude for each user individually, because they offer a single, fixed guidance rate which is only optimal on average for the population. Also, our embodiment 2 lets users freely choose their respiration rate which may not be close to the personal optimum at all. Given both arguments above, we decided to develop a fully adaptive closed-loop system that guides the user's breathing according to an adaptive policy intended to maximize HRV amplitude.

The solution we propose can detect in an adaptation phase, for each user, which respiration rate induces the highest HRV amplitude, and then offers that specific respiration rate during a guidance phase. In this system, again the user lies on the blanket as before in the two other embodiments. The system consists of a number of hardware and software components; see also Figure 6. The bio-signal values (RSP Rate, HRV) are measured using a portable Nexus-10 device with the following sensors attached: a

photoplethysmograph (PPG) for measuring the heart signal (in the form of finger blood-volume pulse - BVP), and a respiration belt used to measure the respiration signal.

On a separate PC are running a data acquisition application, a Matlab application to analyze for real-time analysis of the bio-signals, and a C++ application for controlling the Touch Blanket. The Nexus sends its data to the PC via a Bluetooth connection. The Matlab application receives in real-time the raw bio-signal data from the data acquisition application, and then calculates in real-time the bio-signal features for respiration (such as mean respiration rate) and HRV. The features are calculated every 10 seconds, averaged over a window over the last 30 seconds. The Matlab application transmits every 10 seconds the feature values to the C++ client via a TCP/IP socket.

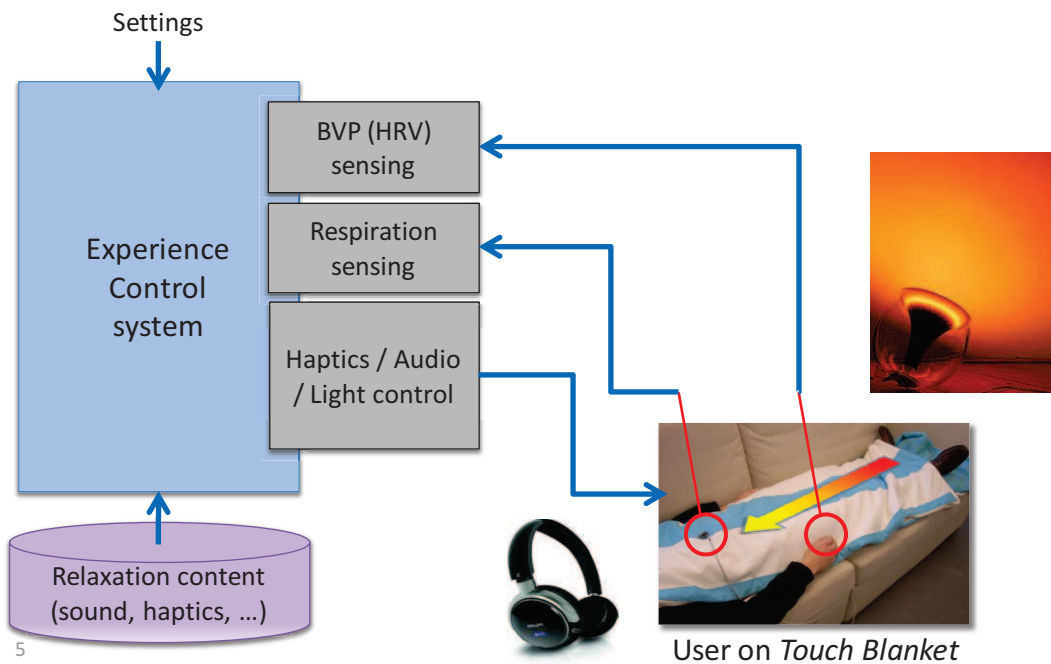


Figure 6 – Simplified system diagram of embodiment 3, a closed-loop adaptive breathing guide that uses respiration and HRV sensing to detect the optimal user respiration rate. The heart signal (BVP) is measured at the finger through a photoplethysmograph (PPG) clip-on sensor.

The C++ application receives in real-time the bio-signal data features from the Matlab application, calculates the optimal respiration rate based on the history of values of bio-signal features, and controls the Touch Blanket, light and audio which constitute the breathing guidance. Notable here again is that the current implementation does not provide explicit indications of the user's performance level, however such options could include pleasant sounds or vibrations when the user succeeds to follow the guide or when the exercise was successful.

Algorithm

The algorithm of the closed-loop breathing guide implements a strategy for guiding the user towards lower respiration rates, while constantly checking the effect of each progressively lower respiration rate on the HRV amplitude values which we intend to maximize. For each new respiration rate that the guide provides, the user is given in total at most 2 minutes time to adapt and follow the guide (initially 60 seconds, and 60 seconds for a retry only if necessary). The 60 seconds have been chosen as a threshold given that previous experiments with breathing guidance showed that 60 seconds is usually enough time to determine whether a user follows the guide, and in total 2 minutes are enough to determine if the user is able to follow the guide at the current respiration rate, or not. We allowed an error margin of 0.5

cycles/min given that usually users will seldom be able to follow the guide at the *exact* guided respiration rate. In our experience 0.5 cycles/min is an acceptable, realistic margin. Whenever the user is able to follow the guide at a specific respiration rate for 60 seconds, the system reduces the guided respiration rate with a step of 1 cycle/min. We used 1 cycles/min here to provide a smooth, gentle accommodation to a lower respiration rate, while also allowing an accurate enough identification of the respiration rate that renders the maximum HRV amplitude values. The algorithm can be summarized by the following steps:

1. **Adaptation phase:** Initially the system determines the respiration rate (RSP Rate) of the user *UBR* (user breathing rate) before the guided breathing exercise (i.e., the baseline) during a period of 30-60 seconds and sets the guide's breathing rate (*GBR*) to the initial user breathing rate *UBR*.
2. While $GBR \geq 5$
 - a. Over the following period of 60 seconds, while the user follows or tries to follow the guide with the rate *GBR*, the system collects 6 times the values of both RSP Rate and HRV Amplitude. Also the average *UBR* is again sampled.
 - b. If the user can follow the guide (criterion: yes if $UBR \leq GBR + 0.5$)
 - The *GBR* is decreased with a *STEP* value (measured in breathing cycles/min). Typically $STEP = 1$ c/min was used.
 - c. If the user cannot follow the guide, allow a single retry by repeating step 2-a.
 - If retry successful, continue algorithm normally at step 2-b.
 - If retry *not* successful, abort the loop and continue at step 3.
3. Analyze all collected values so far for RSP Rate and corresponding HRV amplitude (if any), and set *GBR* to the RSP Rate which gave the maximum HRV amplitude.
4. **Guidance phase:** In the following 10 minutes continue a guided breathing exercise offering to the user the optimal rate *GBR*.

5 First evaluations

In this section we describe the results of the first evaluations we conducted for each of the previously described embodiments. Per embodiment, the insights we describe here have been inferred from discussions with users who tried the system (including the authors and their colleagues), mainly after informal trial practice sessions and during exhibition displays of these systems. We discuss the advantages and disadvantages of using open-loop versus closed-loop systems as well as our experiences so far in using multimodal stimuli for breathing guidance.

5.1 Embodiment 1 - fixed breathing guide

The first embodiment was tested with about 30-40 users, most of which visitors during a Philips-internal exhibition where the setting did not allow us to use the light stimulus. Our hypothesis for this evaluation was that users would appreciate the combined audio-haptic stimuli and that the breathing guidance (if followed properly) would increase their feelings of relaxation.

The open-loop system described in section 4.2 has the advantage of being easier to implement robustly due to its fixed, predefined execution and absence of on-body sensors. The disadvantage is the lack of automatic personalization. Indeed, some of the users found it difficult to follow the breathing guidance. Unfortunately the feedback related to this problem covered quite a range – from users who found the guide too fast, to those who found it excessively slow, to those who would like another balance in the relative times spent in inhaling/exhaling. This means that a quick fix by simply changing the breathing guidance frequency will not solve these problems.

Could however this issue be ignored? Unfortunately, not. The mismatch between the provided pace and the natural respiration rate of the user can lead to uncomfortable feelings caused by the difficulty to follow the guide, which ultimately diminishes the user experience and overall lowers the chance that the user will get relaxed. While some may argue that slow breathing is unnatural to people and is a skill that needs to be learned, an adaptive system could guide this learning process as well so that a user, in each session, can reach a slow respiration rate that they are still comfortable with. Adaptive guides can identify and take into account the user's personal lowest boundary at the time, whereas fixed guides cannot. Moreover, in the case of users who breathe too slow or too deep when following a fixed guide, the consequences can be even more unpleasant including potential hypoventilation, hyperventilation or dizziness. These considerations could indicate that open-loop breathing guide systems are not the best solutions for providing relaxation.

Considering the multi-sensory stimuli, the user comments revealed that most users found the synchronization between the haptic and the audio waves quite pleasing and useful in creating the right atmosphere as well. By letting some users try it with and without headphones, we found that this subgroup of users agreed that the combination of audio and haptic modalities provides a much more immersive experience than haptics alone.

On the haptic effect itself, it was described by users often as a "strange" and "new" sensation, and usually also "pleasant". The users to which we explained the concept of the haptic effect simulating the motion of ocean waves around the body, all understood the concept. However we did not test yet if users could find out about this analogy for themselves, nor how realistic users thought that the effect was compared to real ocean waves. A few users found it "tickling" and a number indicated it to be "like a very light massage". Only two users explicitly disliked it for being too mechanical and reminding them of a buzzing mobile phone, even after giving them the option to adjust the level of vibration.

The visual stimulus, although being perceived to be relevant for setting the ambiance, was not seen as important. One reason for this is that it did not change during a session and partly due to the tendency of users to close their eyes while breathing and attempting to relax.

5.2 Embodiment 2 - following the user's breathing pattern

The second embodiment (described in section 4.3) was tested with about 8 users. The comments of users regarding the haptic effects and the synchronization between the haptic and the audio waves for this system were similar to the previous embodiment, so we will only focus here on the noteworthy differences with respect to embodiment 1. Our hypothesis for this system was that all problems mentioned above, related to users not being able to correctly follow the guide, would disappear and that users would have an enjoyable and relaxing experience. However, we also expected that part of the users would still choose a too-high breathing rate in the absence of explicit guidance.

The advantages of this closed-loop implementation come from the fact that the system allows users to breathe at their own pace, and use their own natural breathing pattern. At the same time the system provides feedback about the performance of the user by the simple fact that users can feel and hear whether the rate of the waves becomes slower and regular in time or not. However, the current implementation does not include an explicit indication of the user's performance level. A disadvantage is that obviously a closed-loop system is more difficult to implement than an open-loop. We found that the user's respiration pattern is not easy to determine accurately in real-time due to inherent noise in the accelerometer measurements and artifacts related to motion or talking of the user. Also, we still have to investigate whether the vibrations of the Touch Blanket disturb the measurements in any way.

This implies that potentially for some users the feedback is not provided appropriately at all times. On the other hand, some users argued that it is better to guide users in breathing exercises rather than trust them to improve their breathing on their own as is the philosophy of the current breathing-following system. Given this argument, we decided to develop also a fully adaptive closed-loop system (Embodiment 3) that guides the user's breathing according to an adaptive policy.

In practice the breathing following algorithm did not always work for all users, because only a simple "first version" algorithm was used which was not yet optimized based on actual breathing recordings of a larger number of users. However, for users that breathed slowly (< 9 cycles/min), regularly and deeply and did not move nor talk during a session, the breathing following algorithm always worked.

Some users commented on a perceivable delay (or "lag") between their breathing and the haptic/audio effect. One user reported that this small delay had a strong influencing effect on him: it caused him to breathe progressively slower, as if the breathing guide indicated to the user to "hold back" in tempo. This type of effect of small delays is already described in earlier work [20]. Therefore, it may be possible to subtly guide a user towards lower respiration rate even while the system follows the breathing pattern of the user. This would be an interesting topic for further research.

The visual feedback was perceived as interesting, however many of the users who tried the system had a tendency to close their eyes while breathing and attempting to relax. In this situation the visual cues are not perceived. Also one could argue that too many feedback cues could be overwhelming and counterproductive for relaxation. For example, some users who did try to pay attention to all three feedback cues (haptic, audio and visual) found that it required quite a lot of concentration which made it rather hard to actually relax. Another possible cause for these reports could be slight (perceived) timing asynchronies between the various stimuli, but we did not further investigate this.

One last point is that choosing the right color to be rendered by the lamps may be very important. For example some suggested that to set a maritime ambiance blue light should be used, whereas studies in literature [21], [22], [23] indicate that blue light has a general energizing effect. Therefore blue light may be counter-productive to the purposes of a relaxation session. On the other hand, it may stimulate feeling awake and refreshed after a session and in this way add to a positive outcome of the relaxation session. Also personal preference plays an important role in what color of light a user can relax comfortably with. Other options are in simulating naturally occurring situations (e.g. sunset, dawn) or perhaps slowly changing the color to guide the user to a desired end state with associated end color.

5.3 Embodiment 3 - fully adaptive breathing guide for relaxation

The third embodiment (described in section 4.4) was tested with about 5 users, but not yet tested in a fully functional state, due to technical problems. Our hypothesis for this system, which we did not test yet, was that we could expect some problems with not being able to follow the guide during the first (adaptation) phase but that this would be compensated for in the guidance phase where the user would be guided with a personal optimal rate.

As with most closed-loop systems the advantage of this system comes from the fact that it offers a highly personalized solution to users. This is facilitated by the underlying algorithm which should lead to an increase of the HRV amplitude for those users that follow the guide. The current system supports only equal time durations for the inhale and exhale phases, which turned out to be not natural for some users and can become stressful when trying to precisely follow the breathing guide.

During initial evaluation of the system we also discovered a problem in the real-time estimation of the HRV amplitude values, which has not yet been solved to date. This problem caused estimated HRV amplitude values to be higher than the 'actual' HRV amplitude values (i.e. HRV amplitude estimates from a recorded BVP signal calculated afterwards off-line) during the first minutes of operation of the system. As a consequence, the selected breathing guidance rate based on the HRV amplitude was often chosen too high. Therefore we could not continue to test the system more extensively.

5.4 Other evaluation results

A general problem was found with the breathing guide embodiments 1 and 3, which both force a fixed breathing pattern on a user during a period of time. The problem occurs when a user for some reason gets "out of sync" i.e. "out of phase". This can be caused by an occasional deep sigh by the user, or an occasional urge to speed up or slow down a breathing cycle. A possible cause for this user behavior is the need of the body to regulate ventilation to optimal levels of oxygen inflow and carbon-dioxide outflow. In such cases the user's breathing starts to become misaligned to the guidance. The guidance algorithm, in the current implementations, does not detect such cases in order to adapt the guidance back to the user. This requires the user to "catch up" with the system by unnaturally quickening breathing pace, slowing it down, or by holding breath for a while. A fair amount of users find this situation stressful and not contributing to relaxation.

6 Conclusions

6.1 General

In this paper we have presented the “*Breathe with the Ocean*” concept, which envisions a breathing guidance system that induces relaxation by providing an immersive experience where the user is virtually present at an ocean shore. Haptic, audio and light effects are used to convey this experience and to guide the user's breathing. We have described the design and architecture of three embodiments of this concept, and gave a preliminary evaluation based on trial sessions. We discussed the advantages and disadvantages of using open-loop versus closed-loop implementations for these types of systems, as well as our experiences so far in using multimodal stimuli in this application. Although we have verified that multimodal stimuli can be used to create a compelling user experience, we did not compare our approach to other e.g. unimodal approaches in a systematic way.

6.2 Evaluations

Open-loop systems have the advantage of being easiest to realize due to the fact that they implement fixed policies of rendering stimuli and do not rely on bio-sensor input, which in practice adds a source of error to a system. The disadvantage is that these systems do not allow on-the-fly automatic personalization.

Our evaluations show that in the case of breathing guidance systems, a lack of personalization appears to be a significant drawback. This is due to the fact that different users have quite different inhale/exhale patterns and optimal respiration rates. Imposing respiration at a rate and pattern to which users cannot adapt comfortably can induce dizziness, hypoventilation or hyperventilation.

In contrast, closed-loop systems can provide personalization to a certain degree. For this reason the feedback from the users was more positive for the closed-loop implementations, in comparison to the open-loop system, when looking at the breathing guidance aspects. Naturally, as a result of having adaptive policies and requiring sensors, these systems are more complex to implement and test. The most critical and challenging part in providing a truly adaptive guidance is estimating the correct user breathing rate, phase and pattern over time. Pattern here includes breathing depth, inhale/exhale ratio and the durations of the pauses in the breathing cycle.

Regarding the sensory stimuli, the user evaluations revealed that most users found the haptic feedback pleasing, even more so if combined with the audio stimuli. Also they found the synchronization between the haptic effect and the audio ocean wave sounds quite pleasing and useful in setting the atmosphere. The visual stimulus, although being perceived to be relevant for setting the ambiance, did not seem to be as important for providing feedback. This was probably due to the tendency of users to close their eyes while breathing and attempting to relax.

In our view, adapting the rendering to the user in the correct manner is crucial to enabling a pleasant user experience. Failure to do so – even if only during a few moments within a session – can ruin the entire experience.

6.3 Future work

For future research we are considering a number of directions, such as

1. Investigating under which circumstances audio or visual stimuli can significantly increase the enjoyment and effectiveness of haptic stimuli, in the context of breathing guidance systems.
2. Comparing different strategies for breathing guidance in terms of effectiveness and enjoyability. E.g. do we need a system with "out of sync" recovery? Is it perhaps better to only guide the user during brief periods and then let a user breathe in his/her natural rhythm for a while? Are high values of HRV amplitude also linked to the most pleasurable experience, or not?
3. Performing formal user tests with the systems mentioned in this paper. To this end, the robustness and user experience of especially the closed-loop systems would still have to be improved. The initial findings in this paper provide a good lead on what needs to be improved.

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