DESIGNING AUDITORY DISPLAY OF HEART RATE VARIABILITY IN BIOFEEDBACK CONTEXT

Bin Yu, Loe Feijs, Mathias Funk, Jun Hu

Eindhoven University of Technology
Department of Industrial Design
Laplace 32, 5612 AZ Eindhoven, the Netherlands
{B.Yu, L.M.G.Feijs, M.Funk, J.Hu}@TUE.NL

ABSTRACT

This paper presents a set of real-time sonifications of heart rate variability in the context of biofeedback. The objective of the study is to explore new ways in providing biofeedback information rather than the typical graphic displays in medical products. Four different auditory displays were created by mapping heart rate variability to timing variations of the sound. In the experiment, ten subjects completed five tests of biofeedback training with four auditory displays and one graphic display. During all tests, the heart rate variability and respiration data were recorded for evaluation of the effectiveness of biofeedback training. Subjects were also asked to rate their subjective experience after each test. The results suggest that most subjects could achieve a similar training effect with auditory feedback compared to graphic feedback. Although the user experience of auditory feedback did not meet our expectations, some subjects were enthusiastic about the direct auditory feedback. We discuss these results and provide a description of what is learnt from our design explorations.

1. INTRODUCTION

Heart rate variability (HRV) is a physiological phenomenon of variation in time intervals between heartbeats. Heart rate is regulated by the autonomic nervous system, and the balance between its two divisions, accelerating (sympathetic) and decelerating (parasymthetic) systems, produces a complex and ongoing pattern of heart rate variability [1]. HRV could reflect various physiological states such as mental workload, emotional responses, stress at work and concentration on tasks [2]. Previous studies [3] showed that giving users an immediate feedback of HRV data would help them improve awareness of heart rhythm and make subtle changes in their body to achieve a better health. This process is referred to as HRV Biofeedback.

Biofeedback is often referred to as 'bio-mirror' since it enables users to 'see' internal physiological processes. Most of biofeedback systems present feedback (physiological information) in visual forms, for example the graphic display used in [4]. But in the context of stress relief, meditations, deep-breathing training and relaxation exercises, auditory feedbacks have an advantage over visual forms that it can liberate users' eyes from the computer screen and improve user's focus and pleasure during a biofeedback training. With auditory displays, biofeedback sessions can be performed with the eyes closed and in a more comfortable position, which is an excellent condition for relaxation.

The sonification of heart activities is not a new idea. The most common approach for doing this is *parameter-mapping* [5], which links the parameters of heartbeats (HR/HRV) to the parameters of sound. In [6], the authors introduced a heartbeat-responsive music system, in which the heart rate values were mapped to a scaling factor to adjust the tempo and timbre of a piece of music. The works in [7] sonified maternal and fetal heartbeats as musical notes in different timbres, namely a cello and a flute. The variation of heart rates is mapped to the duration of the notes. A similar example could be seen in [8], a heart rate indication system was developed to provide biofeedback by converting heart rate data into a music with pitch and tempo changing in real-time. A more complex *Model-based* sonification [5] of heart rate variability has been explored by [9] for medical diagnosis. In the system, multiple variables of heartbeats data were extracted as a source of musical events, being mapped to the specific pitches with different timbral annotations, such as a "tinkling" sound, or a clarinet-like timbre. In [10], Bernd et.al established three different ways of HRV sonification based on frequency analysis: (1) by mapping LF-HF frequency to MIDI pitch of a constant sound; (2) mapping the amplitude of the filtered signal to the volume of sound; and (3) using filtered signal as the MIDI note control.

In this study, four versions of auditory feedback are designed and integrated into a HRV biofeedback system, which provides real-time feedback by converting the heart rate variability into the sound rhythms. In our design, the timing variations of heart rate are mapped to the variations of rhythm in MIDI notes. We assumed that the biofeedback in the form of sound could also enhance the user experience and contribute to the effect of biofeedback. An experiment was carried out to evaluate the effectiveness of auditory feedback. The results will be presented and discussed in this paper, with the insights from the comments from the participants.

2. SONIFICATION DESIGN

Our goal is to provide the heartbeats feedback information faster. This idea has been explained for visual feedback in [11] using the language of classical PID feedback controllers. In Fig 1 we show a typical tachograms from [11], where the length of each bar represents one heartbeats interval. This is an example of proportional feedback. The tachograms of the Stress-eraser [4] are very similar to this.

Figure 1: *A typical tachograms by plotting successive heartbeats intervals*

Could a similar effect be reached using the auditory modality rather than the visual? In fact it is easy to map heartbeat to timing information: just produce a short tone or ping upon detection of the heartbeat event. But the difficulty is that the difference in the heartbeats (RR) intervals is small compared to the RR intervals themselves. For example, if the average RR interval is 1000ms (i.e., a 60bpm HR), then the typical variation of two successive RR intervals is less than 100ms, which is hard to perceive. Therefore we look for ways of amplifying the differences between the RR intervals, making the difference easier to perceive. Through exploration and experimenting we found four promising audio-forms:

1. arpeggio chords with timing variation,
2. arpeggio chords with emphasis variation,
3. two distinct notes with RR interval delay,
4. stereophonic notes with RR interval delay.

First we present audio-forms 1 and 2, which are easy to explain: each heartbeat is translated into one arpeggio chord of a few hundred milliseconds. We choose major scale arpeggios because minor scales tend to be associated to sadness in western culture and also because [12] found that higher arousal ratings were given during minor mode music than during major mode music.

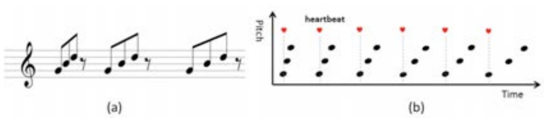

Figure 2: *Slow and fast G chord arpeggios*

For audio-form 1, we created MIDI files for the major G chords using notes G4, B4, and D5, as shown in Fig 2(a). The duration of one chord is *N* times 75ms where *N* is in the range 1 to 10. So, the shortest chord arpeggio is 75ms, which sounds very fast and the longest one is 750ms, which sounds very slow, see Fig 2(b). At each heartbeat one chord is chosen, for which the applicable *N* is calculated by a linear mapping of RR/RR_{avg}. The linear mapping works such that the fastest chord happens when RR/RR_{avg} = 80% and the slowest chord when RR/RR_{avg} = 125%. Here RR_{avg} is the averaged *RR* interval obtained by a first-order low-pass filter with a time-constant of 24 heartbeats (somewhat similar to a moving-window average). If the changes are bigger, the effect is truncated at 80% and 125%, respectively. The effect is that relatively small changes in *RR* variation are translated into better perceivable variations in chord length: an increase in *RR* of 5% for example is mapped to a 20% increase in chord length. At the same time, extreme values will be mapped into truncated ranges at the ends of the spectrum.

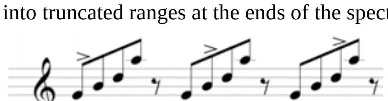

Figure 3: *G chord arpeggios with emphasis on different note.*

For audio-form 2, the timing of the chords does not vary, but one tone is accentuated, i.e., played louder than the others. Each chord consists of notes *G4*, *B4*, *D5*, and *G5*, as shown in Fig 3. The non-emphasized tones are played at 45% volume where 100% refers to the emphasized tone. Although we added already a fourth note to the chord, this still gives a less fine-grained feedback than the previous audio-form. As before, *RR* variation is calculated and then mapped to one of the four possible chords.

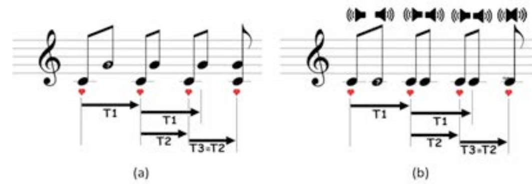

Figure 4: *(a). GC intervals presenting accelerating and steady heartbeats. (b). Stereophonic notes presenting accelerating and steady heart beats*

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

The fourth audio-form is similar to the third, but now using the stereo panorama instead of the different tones, as explained in Fig 4(b). As the heart beat occurs, the *C* is played in the left speaker and a right-panned *C* note is queued to be played later on the right speaker, the queue-delay being set to the most recent RR interval. The effect is a panning transition, going double-note rightward (left *C*–right *C*) when the HR is accelerating, and leftward (right *C*–left *C*) when the HR slows down.

3. EXPERIMENT

In this study, we developed a biofeedback system with pure forms of sound to provide a direct and fast feedback of heart rate variability. We hypothesized that the proposed auditory displays would be a more comfortable and effective interface of the biofeedback system. An experiment was conducted to examine the biofeedback effect of four proposed auditory displays by comparing to a typical graphic display as shown in Figure 1 and described in [11].

3.1 Participants

We designed a within-subjects experiment with ten subjects (five females and five males, age range: 20 to 30). All subjects reported no history of diagnosed cardiac or psychiatric disorders. Participants who were technically unable to use the biofeedback system were excluded from the trial. All participants have never received any medical HRV biofeedback training. All subjects gave the written informed consent and provided the permission for publication of photographs with a scientific and educational purpose.

3.2 Equipment and Measurements

The HRV biofeedback system consists of three parts: bio-signal acquisition module, biofeedback module and sonification module as shown in Fig 5. The pulse signal measured by the pulse sensor is calculated into RR intervals data in the bio-signal acquisition module. Through a USB serial port, the data is transmitted to the biofeedback module on a computer in which RR intervals are translated into sounds or graphics. Considering the context of use, as shown in Fig 6 the biofeedback laboratory served as a dedicated room which provides a quiet environment to receive auditory feedback information.

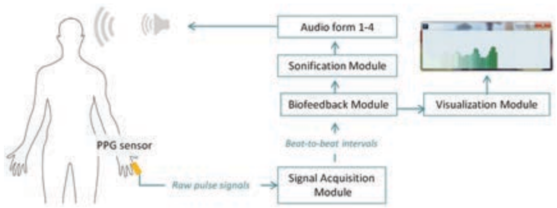

Figure 5: *The HRV biofeedback system developed in the study*

For each participant, the physiological data (pulse and respiration) and subjective perceptions were collected throughout the experiment. The pulse signal was measured by the bio-signal acquisition device developed at TU/e. Respiration signal was recorded by the ANT system *(ANT, the Netherlands)* with a sampling rate of 256 Hz. The respiratory sensor was placed at the chest of the participant and the pulse sensor was placed on the left index finger of the participant, as shown in Fig 6.

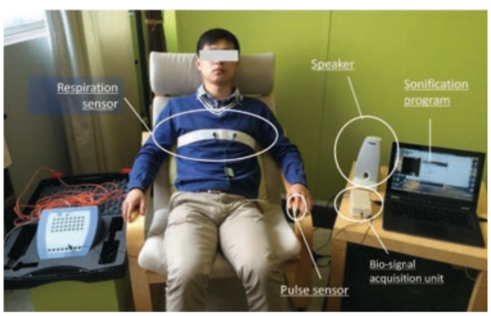

Figure 6: *The experiment setup*

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

3.3 Experiment design

The experiment is designed to answer two questions: 1. whether a similar effect could be reached using the auditory display rather than the visual and 2. which of four audio-forms could be the best one in term of user acceptance and biofeedback effectiveness? Hence, we designed a within-subjects experiment, in which all participants would complete five 10-minute biofeedback tests: four with auditory displays (A1:A4) and the other one with visual display (V1). The experiment randomizes the order of the five tests to counterbalance carry-over effects. The independent variable was the form-giving of the biofeedback given to participants, while the dependent variables were the average HRV value, respiration data, and the subjective ratings.

3.4 Procedures

Before the biofeedback tests, the participant watched a short video instruction to familiarize them with the biofeedback system. A brief introduction was given: *"the purpose of HRV biofeedback is to perceive the variability of heart rate and learn to improve the variability by regulating breathing pattern."* Then, the participant was instructed to relax with natural breathing for 5 minutes. This pre-test resting period is intended to normalize the baseline of HRV and respiration data without biofeedback. Next, the participant would undertake five biofeedback tests separately with different forms of feedback, including four audio-forms and one visual form. Each biofeedback test lasted 10 minutes. The order of the tests was generated randomly.

Before each test, a corresponding video instruction was given to the participants for guiding them how to use feedback information to improve HRV through a breathing regulation. For the graphic biofeedback test, the instructions were:

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

As described above, the design of four audio-forms follows different design principles (see section 2). For the four auditory biofeedback tests, the instructions were different but similar in style. Hence, taking audio-form 1 as an example, the instructions were:

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

After each test, the participants were given a 5-minute break to relax and answer the questionnaire. The pulse data and respiratory data were recorded throughout all five tests. Throughout the experiment, participants were seated comfortably and instructed to move as little as possible. During the auditory feedback tests, participants all were instructed to close their eyes.

4. RESULTS

The qualitative data about the biofeedback effects and the user experience of the auditory displays was collected in the experiment. One-way ANOVA was then used to analyze whether there were any significant differences between the four audio-forms and the visual form.

4.1 Users' perception

The results of the participants' subjective ratings on user experience of each audio-form are shown in Figure 7. In terms of "Clarity of feedback", the score of the visual form (V) is significant higher than audio forms 2, 3 and 4 (A2, A3, A4) (p<0.05; A2, A3, A4 *vs* V1). In terms of "Comfort of feedback", the score of the audio-form 3 (A3) was significant lower than the visual form (p<0.05; A3 *vs* V1). The overall score of audio-form 3 was significantly lower than the visual form. (p<0.05; A3 *vs* V1).

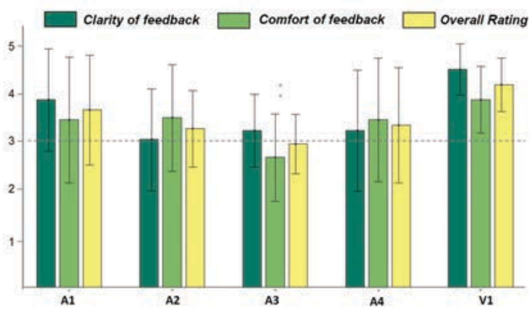

Figure 7: *Results of the participants 'subjective ratings*

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

4.2 Heart rate variability

The SDNN (standard deviation of beat-to-beat intervals) was calculated as the index of the HRV during each test. The SDNN of the pre-test resting period was calculated as the baseline. Comparing the SDNN during the biofeedback tests to the baseline, the improvement of heart rate variability was calculated as shown in Fig.8. The mean values of HRV improvement in each test are denoted with dashed lines, and in biofeedback tests of A1, A2, and V1, the improvements are significant (p<0.05). But there was no significant difference in the HRV improvement among the biofeedback tests.

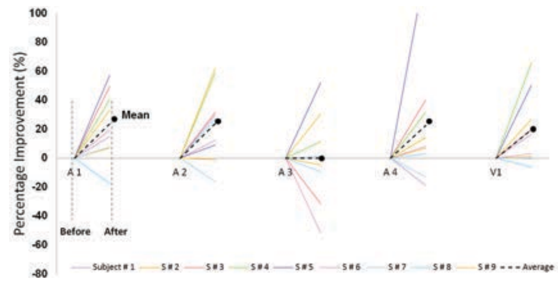

Figure 8: *The improvements of HRV in biofeedback tests*

4.3 Respiration

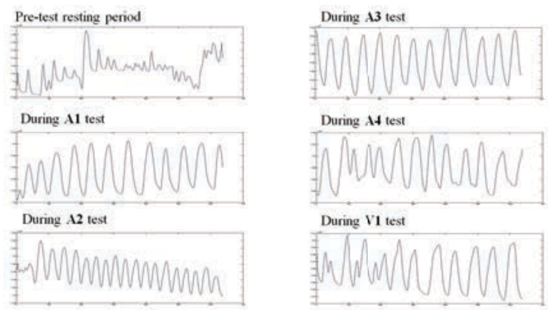

Figure 9: *Typical respiration waveform from one of the participants*

The observation of the respiratory waveform is interesting for understanding how the listeners perceive the feedback and use it to adjust their behaviors. Figure 9 shows the typical respiratory waveforms from one of the participants. During the pre-test resting period, breathing is automatic and unconscious; and in the biofeedback tests, the participant's respiration was regulated towards a deep and regular pattern with both audio and visual forms of feedback. In the tests of A1 and A3, the participant responded to the feedback rapidly and accurately. In A4 and V1 tests, it took the first 1-2 minutes to get familiar with feedback and then reached the same effect. The feedback of A2 seemed to be difficult for the participant to understand and follow, so he failed to follow the auditory feedback, instead he did deep breathing autonomously.

5. DISCUSSION

A natural rhythm in heart rate could be observed when people relax and breathe deeply; on the contrary, this rhythm becomes weak and even disappears when people under constant stress at work. Several attempts [4-11] have been made to present the heart rate rhythm (variability) to individuals through visualization or sonification design. With biofeedback, people could see, hear and even feel the heart rate rhythm (feedback), improve awareness of the rhythm, and then learn to enhance the rhythm. In this study, we proposed four audio-forms based on the similar principle that the variations of RR intervals are mapped to the rhythm of the sound. The different mapping strategies are explored. Audio-form 1 presents heartbeats intervals by changing the intervals between four notes of a chord. It is the most direct mapping approach between timing variations of heartbeats and the sound. Because the rhythm of sound could also be represented by the variations in the positions of emphasis, in Audio-form 2, the emphasis of a G chord arpeggio is being modulated among four notes according to the latest RR interval. Audio-form 3 and 4 use the interval between two successive notes to present the most recent RR interval. In these two forms, the differential of the RR intervals is presented as sound. The results of the participants' subjective ratings on audio-forms show that the listener gave the A1 higher ratings due to its clarity.

The results of heart rate variability support our hypothesis that in a biofeedback session, a similar biofeedback effect (HRV improvement) could be achieved using the auditory displays rather than the visual. Although the clarity and the comfort of the audio-forms still need to be improved, the direct and fast responses of the audio-forms ensure effectiveness for conveying information. With the auditory feedback, individuals received the sound, perceived the information of heart rate variability and learned to regulate the breathing pattern to enhance it. After a few minutes self-regulation with biofeedback, the heart rate rhythm would be enhanced and become gradually distinct, and being linked to a clear rhythm in the sound. The auditory display acts as the "output" of the biofeedback loop, which are important to the human's self-awareness and self-regulation processes. The respiration data also reflected the self-regulation process, and suggested that most participants could adjust their breathing pattern with audio feedback as same as visual feedback during the tests.

As a presentation of information, the clarity of auditory display is crucial for biofeedback effect. Because the variation between two successive RR interval values is too small to perceive, in the sonification, we tried to amplify the differences between the RR intervals, allowing listeners to perceive the heart rate variability as clearly as possible. From participants' subjective ratings on *"Clarity of feedback"* in figure 7, we can see that the graphic display is clearer and easier to follow than the proposed audio-forms. Our explanations for this are as follows. The proposed auditory displays are designed for conveying the variation between two successive heartbeat intervals, but might not be suitable for presenting the rhythm of the variations, which occurs at 0.1 Hz during relaxation. This helps explains why the participants thought it was clearer to perceive the patterns of HRV through the visual display, see figure 1.

In terms of *"Comfort of feedback"*, the ratings on auditory displays are generally below the visual display. The participants were questioned regarding the subjective feelings of stress, tiredness and sleepiness. In order to go deep into the reason for the low ratings of audio-forms, we analyzed the score of each item and found that the participants gave the audio-forms high marks on "stress". In other words, they were feeling more pressure with the audio feedback. One possible explanation we obtained is that the unfamiliarity with the novel audio-forms increased learning difficulty that caused a psychological burden to users. Compared to music or sounds of nature, the proposed audio-forms are not common in daily life. We believe there is a possibility that if the participants may get more exposure to the auditory feedback, after they are accustomed to the audio-forms, they might be able to accept and execute more easily.

For biofeedback purposes, the transparency would be a priority for sonification design. The clarity of feedback is crucial for users' understanding of biofeedback loop. Meanwhile, the sonification should strive for a good sound design, which is "meaningful", "pleasant" or can refer to aesthetic considerations. During the previous experiment, the participant's behavior (breathing) was modified by the presence of the audio feedback, but they were still unable to relax down mentally. We think, through different levels of the interpretation biosignals, biofeedback may be presented in an explicit way (for example: the direct-mapping in this study) or in a more implicit way (for example in [16]). In a future work we wish to "add" more elements (from music or natural sounds) into these pure sonifications. We want to investigate how to make the biofeedback could be perceived as clear and pleasant by the listeners.

6. REFERENCES

[1] H. M. Stauss, "Heart rate variability," Am. *J. Physiol.-Regul. Integr. Comp. Physiol.*, vol. 285, no. 5, pp. R927–R931, 2003.

[2] B. M. Appelhans and L. J. Luecken, "Heart rate variability as an index of regulated emotional responding," *Rev. Gen. Psychol*., vol. 10, no. 3, p. 229, 2006.

[3] P. M. Lehrer, "Biofeedback training to increase heart rate variability," *Princ. Pract. Stress Manag.*, vol. 3, pp. 227–248, 2007.

[4] F. Muench, "The Portable StressEraser Heart Rate Variability Biofeedback Device: Background and Research.," *Biofeedback*, vol. 36, no. 1, 2008.

[5] H. Thomas, A. Hunt, and J. Neuhoff, *The Sonification Handbook Berlin,* GE: Logos Verlag, 2011.

[6] G. McCaig and S. Fels, "Playing on heart-strings: experiences with the 2Hearts system." *Proceedings of the 2002 conference on New interfaces for musical expression*, pp. 1-6, 2002.

[7] V. Avbelj, "Auditory display of biomedical signals through a sonic representation: ECG and EEG sonification," In *MIPRO, 2012 Proceedings of the 35th International Convention*, pp. 474-475. IEEE, 2012.

[8] K. Yokoyama, J. Ushida, Y. Sugiura, M. Mizuno, Y. Mizuno, and K. Takata, "Heart rate indication using musical data," *Biomedical Engineering, IEEE Transactions on*, vol. 49, no. 7, pp. 729–733, 2002.

[9] M. Ballora, et al. "Heart rate sonification: A new approach to medical diagnosis." Leonardo vol. 37, no.1 pp. 41-46, 2004

[10] M. Falkner and D. M. B. Orzessek, "Sonification of autonomic rhythms in the frequency spectrum of heart rate variability." *Proceedings of the 12th International Conference on Auditory Display, London, UK,* pp. 272–274, 2006.

[11] L. Feijs, G. Langereis, and G. Van Boxtel, "Designing for heart rate and breathing movements," *Des. Semant. Form Mov.*, pp. 57.2010.

[12] D. van der Z. Marjolein, H.D.M. Westerin Joyce, and van den Broek Egon L., "Emotional and psychophysiological responses to tempo, mode, and percussiveness.," *Music. Sci*., vol. 15, no. 2, pp. 250–269, 2011.