Can Changes in Heart Rate Variability Represented in Sound be Identified by Non-Medical Experts?

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ABSTRACT

Heart rate variability (HRV) has become a wide-spread area for the investigation of the health and stress states of individuals. This paper aims at exploring the effectiveness of representing HRV measures with alternative modalities, other than visual displays, such as audio or haptics. Therefore, we undertook a preliminary study in which we applied a parameter mapping sonification approach to transform the HRV signal into an audible form. In this work, we sought to evaluate the human perception of the developed auditory interface. Hence, a dataset that involves interbeat interval measurements of individuals experiencing changes in mental state in the form of meditation was selected as the basis of the study. The HRV parameters of the dataset were mapped to acoustic features using a linear mapping technique. The feasibility of the system was assessed by measuring the learnability, performance, latency, and confidence aspects. The results suggest a great potential of incorporating auditory displays in the analysis of HRV. Participants were able to distinguish the different meditation states and types with minimal training time. However, further studies should be conducted on a larger population to provide verification of the findings of this preliminary study.

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KEYWORDS
HRV; heart rate variability; sonification; auditory display; parameter mapping

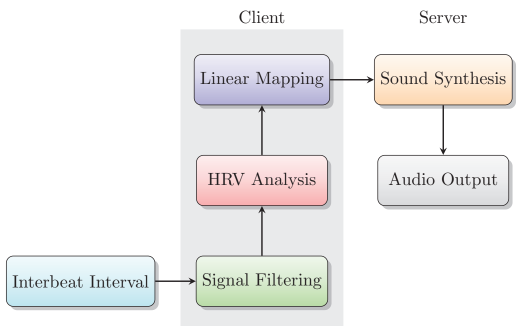

Figure 1: High-Level Architecture

$$y_{value} = \frac{x_{value} - x_{min}}{x_{max} - x_{min}} \times (y_{max} - y_{min}) + y_{min}$$

Equation (1): Linear Mapping

where $[x_{min}, x_{max}]$ is the source range resulting from the HRV analysis and $[y_{min}, y_{max}]$ is the destination range reflecting the sound parameter's range.

INTRODUCTION

Over the last few decades, heart rate variability (HRV) has become a vital non-invasive indicator of state of health as it reflects the balance of the autonomic nervous system (ANS) [1]. HRV is determined by measuring the time intervals between successive heartbeats, (by measuring the time between the same points in successive ECG wave-forms, typically each interbeat interval), over a period of time. An unusually low or high value of HRV implies that a person suffers from health issues, physical stress [9] or mental stress [3, 4]. One of the prevalent mental practices affecting the cardiovascular system and ANS is meditation. Hence, various studies examined the impact of meditation on HRV [5, 13]. It has been observed that during meditation the heart rate decreases, resulting in an increase of the HRV score. Currently, cardiac activity and most biomedical signals are conveyed with a visual representation. However, the visual sensory capacity is often overloaded especially in clinical environments. [14] discussed the improvement of task performance when the information is distributed across multiple sensory channels, such as using audio or haptic interfaces. The development of auditory display involves mapping the data to acoustic parameters, which is known as sonification [8]. This can be achieved with various methods including parameter mapping and model-based techniques [6]. Several studies were conducted to evaluate the representation of physiological signals with audio [2, 12], or haptic [10]. Therefore, this paper aims at investigating the effectiveness of representing HRV data with auditory interfaces as a supplement or a complement of visual displays. The study will place emphases on improving the experience of the subject in monitoring and analysing HRV data from an HCI perspective.

PROTOTYPE DEVELOPMENT

The initial development of the HRV sonification approach comprises three main subsystems: interbeat intervals as data input, a client responsible for the processing and analysis, and a server to produce the output audio file as depicted in Figure 1. First, the HRV signal undergoes basic filtering process to remove any extreme artefacts due to the presence of noise based on a symmetrical averaging algorithm. Subsequently, the HRV analysis is performed on the filtered signal in time and frequency domains. The analysis algorithm is based on an overlapped-sliding window approach with a predefined window size and a short time increment as discussed by [15]. The major advantage of using a sliding window approach over conventional analysis is the accuracy of the dynamic changes of the HRV. Then, a linear parameter mapping approach was considered to convert HRV measures to sound parameters. Since pitch is the sound parameter most commonly used in parameter mapping sonifications, each calculated value from the analysis (x_{value}) is mapped to a certain pitch value (y_{value}) based on Equation (1). Lastly, the series of mapped pitch values are sent to a sound synthesis application to generate the corresponding audio track.

EVALUATION

Study Design

To assess the auditory display, an online existing dataset from Physionet[1] was used. It includes recordings of two types of meditation which are yoga and Chinese Chi [11]. Each meditation type consists of two states: pre-meditation and during meditation. Therefore, each meditation state was mapped to a series of pitch values. To discriminate the type of meditation, yoga and Chi were mapped to different timbres based on the non-linear analysis discussed by [5]. The yoga was mapped to a pure tone; generated from a sine function while the Chi was mapped to a sharp tone produced by a triangular function. This mapping was considered to be intuitive, because the smoother, sine wave mapping represented relatively quiet meditation, whereas the sharper, triangular wave represented more energetic exercise. Hence, this study aims at exploring the participants' ability to distinguish the recordings of different meditation states from the HRV analysis parameters. Moreover, to observe if the participants can perceive the type of meditation by listening to the produced sound. (see Hypothesis1)

Hypothesis 1. *The sonification of HRV parameters can effectively convey information indicating the current state of the meditated individuals.*

[1]https://physionet.org/physiobank/database

Procedure

The experiment session was divided into three main phases: introduction, training, and evaluation. In the first phase, participants were introduced to the experiment by presenting examples of low/high pitches and pure/sharp tones. The second phase involved a 10-minute training session to familiarise themselves with the testing environment. It consisted of a pair of recordings for different states for the same meditation type with a 5-second gap. Afterwards, two questions were displayed to the participant asking about the meditation type (Chinese Chi or yoga) and the sequence of states ((1)pre-, during meditation/ (2) during, pre-meditation). The training was repeated until the participant answered all questions correctly. The last phase started similar to the training, but with six sets of soundtracks composing of three yoga and three Chinese Chi meditations presented to each participant in a random order. In the last two phases, the number of correct responses and completion time were recorded. Finally, the participants had to complete an online survey by answering the post-test questions. The questions focused on exploring the confidence level in making the decision and the overall experience.

Participants: Fifteen participants (8 Female, 7 Male) took part in this study. Their age ranged from 20 to 44 years. They were asked in a background survey to rate their familiarity with topics related to the study on a scale of 1 to 5. On average, they rated their experience with sonification and auditory displays as 3 with a standard deviation of 1.8 .

RESULTS

The feasibility of auditory displays in the context of HRV was evaluated based on four measures: (1) the **learnability** of the sonification approach, (2) the overall **performance** in terms of accuracy, (3) the **latency** by measuring the required time to make a judgement about the meditation type, and (4) the **confidence** with which the decisions were made.

Table 1: Learnability Measures

	Time (min)	Repetitions
N	15	15
Min	1.15	1
Max	6.53	6
Mean	3.05	2
STD	1.88	1.46

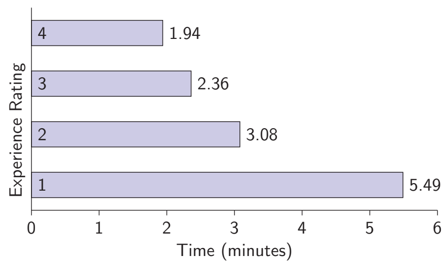

Figure 2: Average Training Time based on the Experience Ratings

Actual Type	Classified Type: Yoga	Classified Type: Chi	Total
Yoga	44.4%	5.6%	50%
Chi	15.6%	42.2%	50%

Figure 3: Confusion Matrix for the Meditation Type

Actual Sequence	Classified Sequence: Seq. [1]	Classified Sequence: Seq. [2]	Total
Seq. [1]	34.5%	11.1%	45.6%
Seq. [2]	4.4%	50%	54.4%

Figure 4: Confusion Matrix for the Sequence of Meditation States

Learnability

In the field of auditory displays, the users should easily learn the association between the sounds and their referents to deliver an effective solution. The participants spent an average of 3 ± 1.88 minutes in the training session with a minimum and maximum duration of 1.15 and 6.53 minutes, respectively. Regarding the number of trials necessary to reach a 100% score in responses' accuracy, 8 participants (53.3%) were able to identify the meditation states and types correctly from the first training trial. Whereas, five participants (33.3%) passed the training session from the second or third trial. From Figure 2, it can be observed that participants with high experience ratings in auditory displays tend to complete the training faster.

Performance

To examine the categorisation task performance, classification tables in the form of confusion matrices were constructed to calculate the accuracy rate, sensitivity, and specificity. In this study, the accuracy corresponds to the number of correct responses, which measures the participants' ability to differentiate the meditation types and states correctly. Firstly, the accuracy rate of the meditation type is relatively high 86.6%. Figure 3 demonstrates the confusion matrix in which the derived specificity score is 88.8% (Yoga) and the sensitivity score is 84.4% (Chinese Chi). It has been noticed that most participants responded incorrectly when the first played track pair was for the Chi meditation. After listening to the Yoga, they were able to answer the subsequent questions correctly. This issue can be resolved by associating better descriptive timbres based on the sonified data or by extending the training period or trials. Secondly, with regards to the accuracy rate of the meditation states, participants received an overall percentage of 84.4% in identifying the sequence based on the pitch difference. In general, for both meditation types, the accuracy of the second sequence (During, Pre) was higher than the first sequence (Pre, During) with percentages of 91.84% and 75.61%, respectively. Figure 4 shows the confusion matrix of the meditation states. Overall, the accuracy of classifying the meditation types and states based on the developed auditory interface was 85.6%.

Latency

The latency of the classification was measured based on the time taken for the participant to decide on the meditation type. On average, the participants' response times of yoga and chi were 3.56 and 4.50 seconds, respectively. The results indicate that participants responded to yoga questions faster; this could be due to the natural familiarisation with the pure tone as compared with the sharp tone.

Confidence

Assessing the certainty of the listeners in making the decision about the sonified data is essential to develop an effective auditory display. Hence, the participants were asked to rate their confidence level on a 5-point Likert scale (1: Low, 5: High) when answering the two questions. The weighted averages for the meditation type and states were equal to 4.27 and 3.87, respectively. The results suggested the participants had a higher confidence rate in distinguishing the different timbres, pure and sharp tones. Based on the participants' feedback, the pure tone (yoga) was easily perceived as compared with the sharp tone.

DISCUSSION AND FUTURE WORK

The study aimed at evaluating the HRV sonification system in the context of meditation, it is considered as a preliminary stage to assess the human's perception of interpreting HRV parameters in audio interfaces. In general, it is important to minimise the learning time while maintaining a high accuracy rate to gain an advantageous auditory display system. The results of the study showed that the participants required a basic training of an average of 3 minutes to an accuracy score of 100%. Although some participants reported that they had to memorise the mappings of pitches and timbres, they had their strategies in developing the different associations with the meditation type and states. However, [7] found that giving more time in the stage of auditory familiarisation leads to improving the overall learnability process. The primary evaluation measure was the classification accuracy of the developed auditory display. The analysis outcomes show high accuracy rates where participants were able to distinguish the different soundtracks reliably. However, the overall performance can be significantly enhanced by improving the mapping technique and incorporating other acoustic parameters. Furthermore, the timbre mapping can be enhanced to provide an intuitive and better classification. With regards to the latency aspect, measuring the delay helps in assessing the appropriateness and practicality of auditory displays in real life applications. Thus, examining how fast the user could potentially respond. The response time in this study was minimal; less than 5 seconds. However, the latency requirement can be varied based on the criticality of the user's response to the application.

For future work, we plan to enhance the mapping technique; thus an advanced auditory display can be developed by considering the multi-dimensionality characteristic of the sound. Further studies can be conducted to compare the efficacy of auditory displays against visual displays under certain circumstances. For instance, exploring the user's monitoring performance of both interfaces in a cognitively loaded environment. To extend our research, we plan to investigate the possibility of developing a haptic interface to convey the HRV signal. The design of tactile modality should involve several experiments to find the appropriate intensity, pattern and rhythm. The benefits of incorporating a third modality may deliver a quick response and an accurate detection for certain conditions.

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