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ORIGINAL PAPER

Design and evaluation of the effectiveness of a sonification technique for real time heart-rate data

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Abstract This article is motivated by the question "Can a sonification system that provides continuous auditory heart rate feedback help stabilize an athlete's heart rate at a given target heart rate while exercising?" The sonification system uses a *Polar H7* heart rate sensor to measure the heart rate of the athlete and an *iOS* device for its processing and display. We implemented several sonification approaches, of which two were tested in both a unimodal and an audiovisual context in comparison to a purely visual feedback and to not having any feedback. The system's objective performance and multiple subjective usability aspects were evaluated in an experiment with 16 subjects. The experiment has to be considered a pilot study because the exercising conditions were artificial. The subjects were exercising on an indoor cycle and could focus their visual sense on the visual display all the time. It was found that all of the feedback methods could convey information to the athlete and were therefore clearly superior to not having any feedback. The failure of showing a supremacy of the multimodal methods over the purely visual one can be reasoned by the fact that the testing conditions were artificial and could therefore not show the advantages of auditory/audiovisual feedback due to limited bandwidth of the visual channel. The conclusions we make about the design and evaluation of such sonification systems can be considered a useful starting point for further work in this field.

Keywords Heart rate · Sonification · Biofeedback · Athletes

1 Introduction

1.1 Background

Since the introduction of wireless heart rate monitors, professional and amateur athletes alike have used them with great success to optimize their training regimen [4]. A heart rate monitor provides real-time information to athletes, which can be helpful in fine tuning aspects of a workout, such as training intensity, training time, recovery time, etc. Thus, having such a real-time heart rate information as a feedback may help an athlete to train better, ensuring less injuries, better performance and shorter recovery times.

Most of the professional quality real-time heart rate sensors can monitor the instantaneous heart rate of a user and transmit the information to an app on a smart phone or a watch. The phone or watch can be used as a visual display for the heart rate information. The most common feature is a real-time visual display of the current heart rate (usually in beats per minute) to the user. Such a feedback allows an athlete to either increase the intensity of training or reduce the effort in order to stay in "exercise zones". A major disadvantage of such visual feedback is that the main sensory input of vision is occupied (as in sports such as running or biking), thus preventing an athlete from frequently looking at his/her visual feedback display.

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1.2 Related literature

In his work [2], Burke scientifically describes the advantages of using heart rate monitoring in sports training. To develop efficient heart rate monitoring systems, it is crucial to know the applications and the limitations of such systems.

Sonification has been used in various sports and physical activities to give feedback to the user about their state of body or performance levels. Wärnegård describes a sonification method using *libpd* for Android OS to create auditory warning clues in real-time to aid athletes when their heart rates exceed or fall below certain limits [17]. Godbout et al. [3] used a rhythmic sonification and audio feedback method to co-ordinate an athlete's movements. Their proposed use of phase triggered sound events to sonify rhythmic events may have a lot of potential in sports such as rowing, running, etc. This method was created as a prototype for the Armour39 challenge in 2013. Schaffert et al. [15,16] describe a sonification method for synchronized rowing to aid a team of rowers to row faster. The acceleration time trace is sonified and given as an acoustic feedback to rowers, enabling an increase in mean velocity of the boat. This method was tested on professional rowers from the German Rowing Association.

Another purpose of sonification of the heart rate is in the medical field. Mihalas et. al [11] present an auditory display of the heart rate while exercising for either clinical settings or self-monitoring applications. There exist several approaches to an auditory display of heart rate variability (HRV): Orzessek and Falkner [12] developed a musical real-time biofeedback system that aims to help patients become aware of their inner activities. Yu et al. [18] also use a musical sonification for this purpose and evaluate the system in an experiment. It could be shown, that subjects were similarly successful in controlling the heart rate variability with an auditory and a visual feedback. However, the auditory feedback was not considered as comfortable as the visual feedback in this study.

Furthermore, Barrass and Best [1] examine psychoacoustic aspects of stream based sonification. This reference can be useful when designing a continuous heart rate sonification that is used in combination with other auditory biofeedback methods.

1.3 Proposed system and research motivation

In this article we propose a rather *continuous* sonification feedback method for athletes using heart rate monitors for exercising. Although current heart rate monitoring systems which give auditory feedback to the user using discrete time auditory clues exist, they give continuous feedback only visually [17]. As previously mentioned, this visual feedback is not optimal when an athlete is doing an activity, where the eyes cannot be focused on the visual display all the time (e.g. running or biking). Furthermore, by combining the auditory display with the visual display, one might be able to provide an enhanced feedback to the athlete by conveying redundant information on different channels. The athlete might get a better overview of his/her heart rate course and therefore be able to use the feedback in a more purposeful way.

We intend to use the proposed method as a platform to propose future sonifications which may indicate trends, deviation from a target heart rate, allow the user to follow a performance curve, etc.

1.4 Overview

Section 2 describes the hardware used, software developed and the overall setup used for the feedback system. In Sect. 3 we describe the two sonification models proposed in this article. Section 4 describes the experimental setup, the mode of testing our algorithm and the participant demographics. We analyze the results in Sect. 5 and conclude the paper with some insights and directions for future work in Sect. 6.

2 Sonification for real-time heart rate monitoring

2.1 System description

The block diagram of our system is shown in Fig. 1. The athlete straps on a heart rate sensor to his/her chest and starts exercising. The sensor has a wireless connection to a smart phone or tablet. The analysis of the heart rate information and sonification is performed in the tablet. The athlete gets a sonified feedback about his/her instantaneous heart rate through headphones and visual feedback via the tablet display. The athlete may use the sonified feedback to control the athletic effort. The whole system can be considered a control loop where the athlete generates the data, i.e. the heart rate, and gets auditory and visual feedback and controls the effort accordingly.

2.2 Hardware and software description

For our work, we used the *Polar H7* real-time heart rate sensor shown in Fig. 2. The sensor has a strap that fits around a user's chest. To this strap, the sensor snaps on with 2 buttons. The sensor uses the *Bluetooth Low Energy* protocol to communicate with other devices whose hardware and drivers support the *Bluetooth 4.0* standard. The sensor sends unfiltered as well as filtered R–R interval information (an integer heart rate value in beats per minute) once every 997 ms.

We used an *iPad* for processing and displaying the heart rate information. The entire app for the heart rate monitoring system was programmed using *Objective-C*. We used the processing power of the tablet to synthesize the sounds used

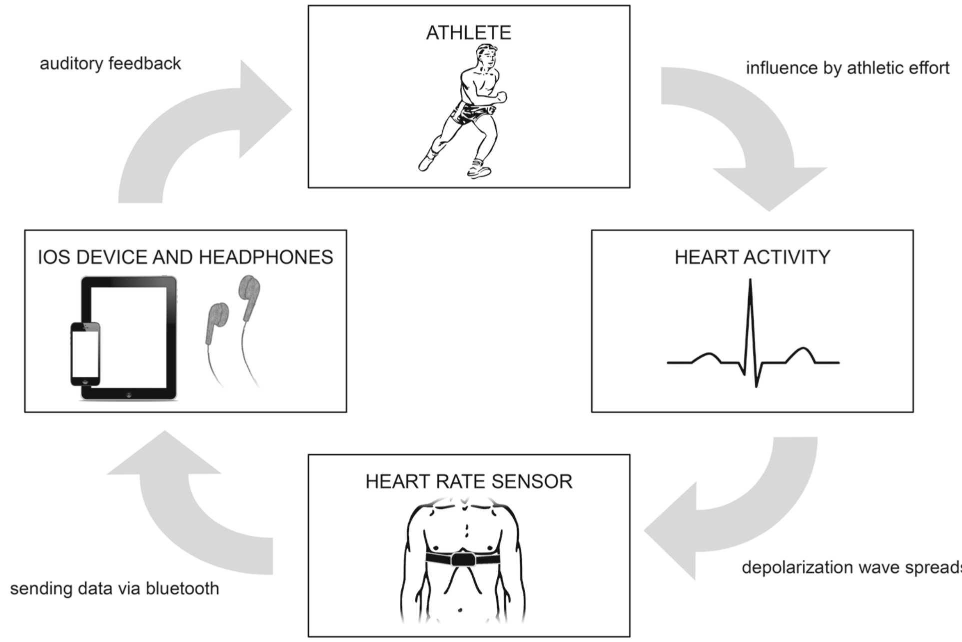

Fig. 1 Block diagram for the proposed system

Fig. 2 Polar H7 sensor

in the sonification scheme using *Csound* as our platform. Csound is a popular language for algorithmic synthesis tasks and is easy to interface with other programming languages such as C. Thus, the app uses Objective-C to monitor the heart rate and based on the instantaneous heart rate, communicates with Csound using the Csound iOS API and outputs a sonified audio. To deliver sound to an athlete as he/she exercised on a sports bike, we used *Monster iSport Victory* sports earphones. More details about the testing modalities are described in Sect. 4.

2.3 Latency in heart rate monitoring

Depending on the used feedback method, the full update latency (time, until a change of the heart rate can be noticed in the feedback) of our sonification system is maximum 3650 ms + audio processing time (but clearly lower for most of the time). The maximum latency of the Polar H7 heart rate sensor is 1000 ms (depending on the synchronicity of the detected heartbeats and the sent data packets. For the pitch mapping sonification approach (see below in Sect. 3.1), which repetitively conveys information to the user at a period of 2650 ms, the latency is highest. Audio processing time is negligible compared to the latency of the other components, the Csound iOS API latency is clearly below 100 ms. We consider the systems latency suitable for exercising because the changes in the human heart rate caused by changes of the effort are relatively slow. Changes of the effort result in fluctuations of the heart rate around the target heart rate with rise and fall times of about several tens of seconds (see below in Fig. 8).

2.4 Data description

Our aim is to sonify heart rates for athletes to use as feedback during training. In order to estimate an athlete's target heart rate, we have to determine the "target zone" which measures the training intensity in terms of heart rate. This can be estimated using an individual's maximum heart rate (HR_{max}), resting heart rate (HR_{min}) and age ($\mathcal{A}$) [17].

To determine an athlete's resting heart rate, the heart rate is measured for a short duration of time when the athlete is in a resting position and an average value is calculated. This is denoted as HR_{min}. The maximum heart rate an athlete can achieve is the heart rate achieved at 100 % training intensity. This can be estimated best during a stress test, but such an effort is beyond the scope of this project and hence we turn to studies which estimate the HR_{max} as a function of the athlete's age. The formula for maximum heart rate is given as [14]

$$HR_{max} = 205.8 - 0.685 \cdot \mathcal{A}. \quad (1)$$

The target heart rate (HR_{target}) is the heart rate at which an athlete should exercise for a certain training mode (such as aerobic, anaerobic, interval endurance training, etc.). It is thus a function of the training mode. There are several methods to compute the target heart rate. We discuss two methods here, namely Karvonen method and $\%HR_{max}$ method. In the Karvonen method [6], we define a quantity called the "heart rate reserve" (HRR) as

$$HRR = HR_{max} - HR_{min}. \quad (2)$$

Now the target heart rate is defined as a quantity which scales between HR_{min} and HR_{max} based on training intensity $\mathcal{T}$ (value between 0 and 1) as

$$HR_{target} = HR_{min} + HRR \cdot \mathcal{T}. \quad (3)$$

In the $\%HR_{max}$ method [7], the target heart rate is calculated as a percentage of HR_{max} without taking the resting heart rate into consideration. In this method, HR_{target} is defined as follows ($\mathcal{P}$ is the percentage of the maximum heart rate with typical values between 0.5 and 1).

$$HR_{target} = HR_{max} \cdot \mathcal{P} \quad (4)$$

As given in Table 1, training at various intensities has differing benefits.

3 Sonification models

Our goal is to create a sonification method that maps the range between an athlete's resting heart rate and maximum heart rate to an auditory parameter. For this purpose we chose to experiment with three parameters to map the heart rate to:

- Pitch—The heart rate can be mapped to a pitch range with a low anchor frequency representing HR_{min} and the high anchor frequency representing HR_{max}. To achieve a musically linear pitch mapping, the heart rate is mapped to an exponential frequency range.
- Time—The duration of a periodically repeating note can be used as a parameter. The percentage of the time interval which is filled with the note can be used as an indicator of the athlete's heart rate.

The two approaches above allow us to map $\mathcal{H}(t)$ (the instantaneous heart rate) to a pitch or duty cycle, but in order to create a constant HR_{target} anchor for the athlete, we would need to create a second auditory stream. As a modification, we created an approach that maps the difference between $\mathcal{H}(t)$ and HR_{target} in an intuitive way.

- Temporal/spectral completeness—The fundamental idea here is to create a sound stream that is "incomplete" or distorted/disturbed when the athlete's heart rate differs from his/her target heart rate. Once the athlete reaches the target heart rate, the sound stream becomes complete.

Apart from the parameter mapping, the unfiltered R–R interval information transmitted by the sensor is useful for event based sonification, whereby we could create a sound event for each heartbeat. In the course of developing the sonification approaches, we found that the difference between $\mathcal{H}(t)$ and HR_{target} is more important for perception than displaying the heart rate in the range between HR_{min} and HR_{max}. Taking these aspects into account, we designed two sonifications which use the ideas discussed above. One point to note in the following discussion is that all sonification parameters we chose were subjectively set based on data rate and pleasantness of sounds. We chose certain parameters such as onset times, offset times, base frequencies, etc. using simple psychoacoustic principles and musical knowledge.

In the course of this research project, we conducted several pretests with different approaches based on the mapping methods named above. We chose the following methods (Sects. 3.1 and 3.2) for the experiment because they met best the demands we made to our system:

Table 1 Sporting zones, as obtained from the Polar sensor website [13] (shortened)

Target zone	% HR_{max} ($\mathcal{P}$) (%)	Duration (min)	Benefits
Maximum	90–100	<5	Maximal effort for breathing and muscles
Hard	80–90	2–10	Increased ability to sustain high speed endurance
Moderate	70–80	10–40	Enhances general training pace, improves efficiency
Light	60–70	40–80	Improves general base fitness, improves recovery and boosts metabolism
Very light	50–60	20–40	Helps warm up and cool down and assists recovery

- The mapping should be simple and as intuitive as possible.
- No musical knowledge should be required to understand the feedback.
- The feedback should be present in the foreground even in noisy environments. The sound should not be easily maskable by (especially low-frequency) background noise.
- The feedback should neither be boring nor annoying.

3.1 Pitch mapping

We tried several approaches to map an athlete's heart rate to a pitch value. All the methods have, as a common factor, that a note or group of notes is used to represent the most recent heart rate value. Our first approach was to display $\mathcal{H}(t)$ between HR_{min} and HR_{max}. Thus, we played a group of three notes, one followed by another, where the first note represented the resting heart rate, the middle note represented the instantaneous heart rate and the third note represented the maximum heart rate. But in this approach there is a lot of redundancy since the anchor notes corresponding to HR_{min} and HR_{max} do not change. We attempted to remedy this by playing the anchor notes once every four cycles. This became even more confusing for users who confused the anchor notes for events in the heart rate sonification stream.

This led to the idea of playing only two notes periodically, the first corresponding to $\mathcal{H}(t)$ and the second corresponding to HR_{target}. Thus, the athlete has to adjust the first note to match the second note and then he/she would be exercising at the target heart rate. This method still had a little problem: small changes in pitch were difficult to distinguish for most people. Thus, we quantized the pitches so that an athlete could clearly hear whether the first note was lower or higher than the anchor pitch. We used simple sinusoidal tones for the sonification purpose. The sonification is schematically represented in Fig. 3. The signal is played back once in 2650 ms.

Analytically, the signal can be expressed as

$$x(t, \mathcal{H}(t)) = 0.3 \cdot \epsilon(t) \cdot sin(2\pi \cdot f_1(\mathcal{H}(t)) \cdot t) + 0.3 \cdot \epsilon(t - 325ms) \cdot sin(2\pi \cdot f_2 \cdot t), \quad (5)$$

where $\epsilon(t)$ is an envelope function defined as an ASR (Attack Sustain Release) signal, $f_1(\mathcal{H}(t))$ is a frequency dependent on the current heart rate and f_2 is a constant frequency. The envelope function is defined as

$$\epsilon(t) = \begin{cases} \frac{t}{rand(20\,ms, 40\,ms)} & , 0 < t \leq \tau \\ 1 & , \tau < t \leq 275\,ms \\ \frac{13}{2} - \frac{t}{50\,ms} & , 275\,ms < t \leq 325\,ms, \end{cases} \quad (6)$$

where $\tau = rand(20\,ms, 40\,ms)$ is used for the attack time. The attack time is randomized from one period to the next to inhibit tiring of the ears. The function $f_1(\mathcal{H}(t))$ which maps the current heart rate $\mathcal{H}(t)$ to a pitch is given as

$$f_1(\mathcal{H}(t)) = 196Hz \cdot e^{\frac{1}{20} \cdot round\left(\frac{\mathcal{H}(t) - HR_{min}}{HR_{target} - HR_{min}} \cdot 20\right) \cdot log\left(\frac{771\,Hz}{196\,Hz}\right)}, \quad (7)$$

while the frequency f_2 is fixed at $771Hz$.

3.2 Disturbed heartbeat event mapping

In this approach, we sonified the instantaneous heart rate $\mathcal{H}(t)$ using a simple model for the heartbeat. The rate of this periodically played back modeled sound was equal to the measured heart rate of the athlete. To this heartbeat sound, we added a disturbance signal with a loudness depending on whether $\mathcal{H}(t)$ was below or above HR_{target}. When $\mathcal{H}(t)$ was below HR_{target}, a low pitched tone, whose amplitude level was proportional to the difference between the target heart rate and the current heart rate, was added. The same approach was followed when $\mathcal{H}(t)$ was above the target heart rate, but a high pitched tone was used as the disturbing signal. The underlying idea behind this model is that the athlete shall hear only his/her heartbeat at the target heart rate and the disturbing signal shall act as a feedback to aid him to either increase or decrease the athletic effort. The pitch of the disturbing signal indicates the direction of change in effort while the loudness indicates the magnitude of effort needed to converge to the target heart rate. We used a low pass filtered noise and a low pitched sine tone with an envelope shaped similar to an ECG wave for the heartbeat model. For the disturb-

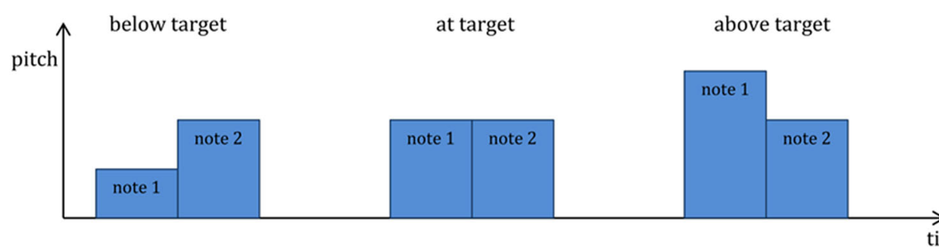

Fig. 3 Schematic diagram of the pitch mapping sonification method

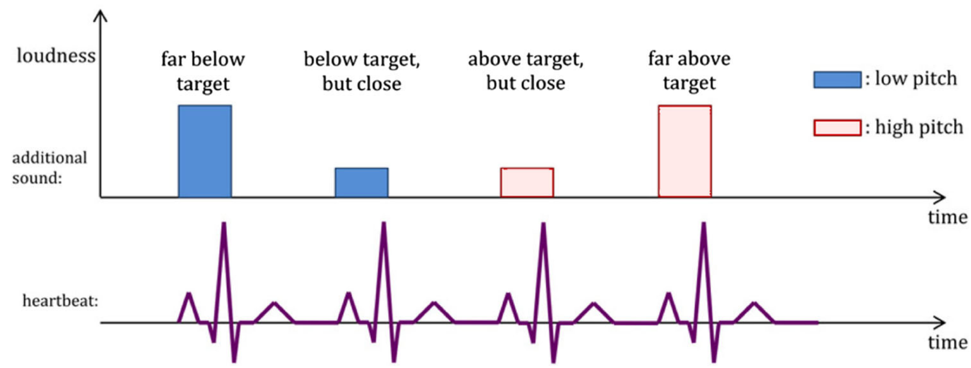

Fig. 4 Schematic diagram of the disturbed heartbeat event mapping sonification method

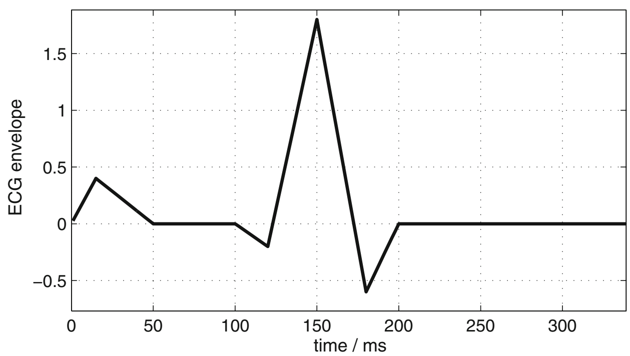

Fig. 5 Envelope of the heartbeat sound

ing sound, we used square waves of two fixed frequencies, a low pitch used for the condition $\mathcal{H}(t) < HR_{target}$ and a high pitch for $\mathcal{H}(t) > HR_{target}$. This sonification method is presented in Fig. 4.

The resulting audio signal can be modeled as shown next. The signal consists of the modeled heartbeat sound and the disturbing square wave sound,

$$x(t) = h(t) + d(t, \mathcal{H}(t)), \tag{8}$$

where $h(t)$ is the heartbeat signal and $d(t, \mathcal{H}(t))$ is the disturbance signal. The signal $h(t)$ is given as

$$h(t) = \mathcal{L}\left(e(t) \cdot [n(t) + 0.5 \cdot sin(2\pi \cdot 60 \cdot t)]\right), \tag{9}$$

where $\mathcal{L}$ is a low-pass operation with a second order resonant IIR filter with a cutoff frequency of 200 Hz and $Q = 1$ and $n(t)$ is a uniform white noise with a maximum amplitude of 1 and $e(t)$ is the ECG envelope signal defined as shown in Fig. 5.

The disturbing square wave sound is calculated as follows,

$$d(t, \mathcal{H}(t)) = [0.02 \cdot l(\mathcal{H}(t)) \cdot s(t, 70Hz) + 0.004 \cdot g(\mathcal{H}(t)) \cdot s(t, 2000Hz)] \cdot e_s(t), \tag{10}$$

where $l(\mathcal{H}(t))$ and $g(\mathcal{H}(t))$ are amplitude control functions, described next and $s(t, f_0)$ is a square wave with the base frequency f_0 and $e_s(t)$ is the envelope function. The envelope function is defined as

$$e_s(t) = \begin{cases} \frac{t}{5\,ms}, & 0 < t \leq 5\,ms \\ \frac{61}{60}\frac{-t}{300\,ms}, & 5\,ms < t \leq 305\,ms \\ 0, & \text{elsewhere.} \end{cases} \tag{11}$$

The function $l(\mathcal{H}(t))$ is defined as

$$l(\mathcal{H}(t)) = \begin{cases} min\left(1, 10^{\frac{-26+130\left(1-\frac{\mathcal{H}(t)-HR_{min}}{HR_{target}-HR_{min}}\right)}{20}}\right) & \text{for } \mathcal{H}(t) < HR_{target} \\ 0 & \text{for } \mathcal{H}(t) \geq HR_{target} \end{cases}, \tag{12}$$

which allows for a low frequency square wave to be played when the heart rate $\mathcal{H}(t)$ is below the target heart rate. Similarly the function $g(\mathcal{H}(t))$ is defined as

$$g(\mathcal{H}(t)) = \begin{cases} 0 & \text{for } \mathcal{H}(t) < HR_{target} \\ min\left(1, 10^{\frac{-26+130\left(\frac{\mathcal{H}(t)-HR_{min}}{HR_{target}-HR_{min}}-1\right)}{20}}\right) & \text{for } \mathcal{H}(t) \geq HR_{target} \end{cases}, \tag{13}$$

which allows for a high frequency square wave to be played when the heart rate is above the target heart rate. Thus we can use the concept of a low frequency or high frequency square wave to provide the information to the athlete about whether he/she is above or below a target heart rate. Also, the level of the square wave being played as a disturbance to the synthesized heartbeat sound is proportional to the difference between the target heart rate and the measured heart rate. At the exact target heart rate, the athlete stops hearing the disturbing sound and thus, this cue allows the user to maintain at the target heart rate.

4 Experiments

To evaluate the usefulness of our system, we tested the sonification approaches described above in a variety of modes. We describe the experiments in detail in this section.

4.1 Research questions and hypotheses

With the experiment we aimed to answer the following questions:

- Can the proposed sonification methods convey heart rate feedback as exact as a state-of-the-art visual display under conditions, where the athlete can focus on the visual display all the time?
- If no, does the auditory feedback help at all with maintaining a steady target heart rate?
- Which of the proposed sonification approaches performs better concerning the subjects' ability of maintaining a steady heart rate?
- Do some feedback methods introduce a bias to the athlete's heart rate, meaning he/she rather tends to over- or undershoot the target heart rate?
- When presented together with the visual display in a bimodal setup, does this lead to a steadier heart rate than the visual-only feedback, when the athlete can focus on the visual display all the time? (e.g. because tendencies in the heart rate might be remembered better)
- Did we succeed in creating an intuitive parameter mapping?
- Might one or both of the auditory feedback methods be unpleasant?
- Would people use the unconventional audiovisual or auditory feedback in their everyday training?

We hypothesized that the auditory only heart rate feedback methods can convey information to an athlete and would therefore help maintaining a given target heart rate. However, we also hypothesized that under the given conditions, the visual heart rate feedback can convey information more exactly and will therefore outperform the auditory-only feedback method. We did not construct any hypothesis about which of the sonification methods would perform better or if methods would introduce a bias. Another hypothesis we made is that a bimodal feedback would outperform a visual-only feedback because tendencies in the heart rate would be remembered better and therefore the athlete has a better overview of his/her heart rate course.

Fig. 6 Experimental setup

Concerning the subjective usability aspects of the sonification methods, we assumed both of our approaches to be intuitive because we had put the main focus on the mapping being intuitive when designing the methods. Since the heart rate sonification is continuous, we took into consideration that the auditory feedback might be partially perceived to be unpleasant, however, we assumed the auditory feedback not to be completely unpleasant, because we had also considered aesthetic aspects when designing the sonification.

4.2 Experimental setup

For testing our feedback methods, a Spin Racer Plus SP-SRP-2802 spin bicycle in a gymnasium in the premises of Fraunhofer IIS was used. The setup is shown in Fig. 6. Participants had to work out on the bicycle and had the iPad in front of them for visual feedback, while they could listen to the sonification of their heart rate through Monster iSport Victory sports earphones.

4.3 Participant demographics

16 participants, all employees of Fraunhofer IIS, took part in the testing procedure. All participants were informed of the background of the test, their personal data and a written consent for use of their heart rate data for research purposes were acquired. The participants were aged between 20 and 43 years (mean age: 28.6 years). 3 of the participants were female and the rest were male.

4.4 Experimental procedure

Each participant was given up to 5 min to get familiar with the testing procedure. The participant could play with the app, the settings of the bicycle and also listen to example sonifications to get a feel for what the objectives were. At the start of the experiment, each subject's resting heart rate was measured by averaging the filtered integer heart rate value over a 30 s period. The subject then exercised on the spin cycle for a 5 min period with the help of one of the methods of feedback. Our aim was to compare the performance of an athlete in such a scenario. The subject exercised for a 5 min period with a particular type of feedback followed by a cooling down period of 5 min, before exercising again with a different method of feedback.

We evaluated 6 different heart rate feedback methods, namely

- No feedback (reference method)—abbreviated as *NF*,
- Visual feedback—*V*,
- Pitch mapping feedback—*PM*,
- Pitch mapping + visual feedback—*V*+*PM*,
- Heartbeat events with loudness mapping feedback—*HB*,
- Heartbeat events with loudness mapping + visual feedback—*V*+*HB*.

Each participant took part in the test with all the feedback methods. The order of the feedback methods was randomized for every participant in order to avoid the systematic bias error caused by learning or tiring effects. The entire testing procedure thus consisted of 6 sessions of 5-min exercises, each followed by a 5-min cooling down period. The cooling down period was also used for filling up a questionnaire on the just concluded exercising session. The cooling down period was necessary to lower the heart rates of the participants between two exercise sessions. Before an exercising session, the subject was briefed about the feedback method and audio examples were presented (in the case of sonification methods). Furthermore to get an understanding of the sonification methods, they could do training sessions for 2 min for the feedback methods that involved auditory feedback. The whole test took a total of around 60 min (including the cooling down periods). The tests were manually monitored by the first author.

The reference method was basically exercising without any feedback, but in order to convey the target heart rates to the subjects, a beep was played once they reached their target heart rate for the first time. In the visual feedback mode, only two numbers were displayed on the iPad - the subject's current heart rate and the target heart rate. For methods involving sonification, auditory feedback was provided to the subject using earphones. The earphones' loudness was set at a constant medium value.

We created an app for every single feedback method that required the subjects to enter their name, age(for maximum heart rate calculation) and their resting heart rate (measured at the start of the experiment) as shown in Fig. 7. The app

Fig. 7 iPad with the app

calculated the subject's target heart rate using the Karvonen method [6] with a constant training intensity of 0.5.

4.5 Questionnaire for the feedback methods

Between two exercising sessions, the subjects filled in a questionnaire on the feedback method used in the previous session. The participants were asked to rate certain aspects of the test on a five point Likert scale [9] with labels "totally agree", "rather agree than disagree", "neither agree nor disagree", "rather disagree than agree" and "totally disagree". The statements for each feedback method were,

- *"The mapping of the heart rate to the sound is intuitive."* (This question did not feature in the "no feedback" and "visual feedback" sessions.)
- *"The monitoring helps me with reaching/maintaining my target heart rate."* (This question did not feature in the "no feedback" session.)
- *"The sound is pleasant."* (This question did not feature in the "no feedback" and "visual feedback" sessions.)
- *"I can focus on the monitoring for a long time without getting tired."* (This question did not feature in the "no feedback" session.)
- *"In this testing session, I was successful in holding my target heart rate for most of the time."*
- *"I like the overall experience of this way of exercising."*
- *"I would exercise in this way in everyday training."*

Furthermore, the subjects were asked to give a ranking to each of the six feedback methods. They were also encouraged to give other comments about the sonification, how they would change it, what they liked about each method, the exercising sessions or the testing methodology.

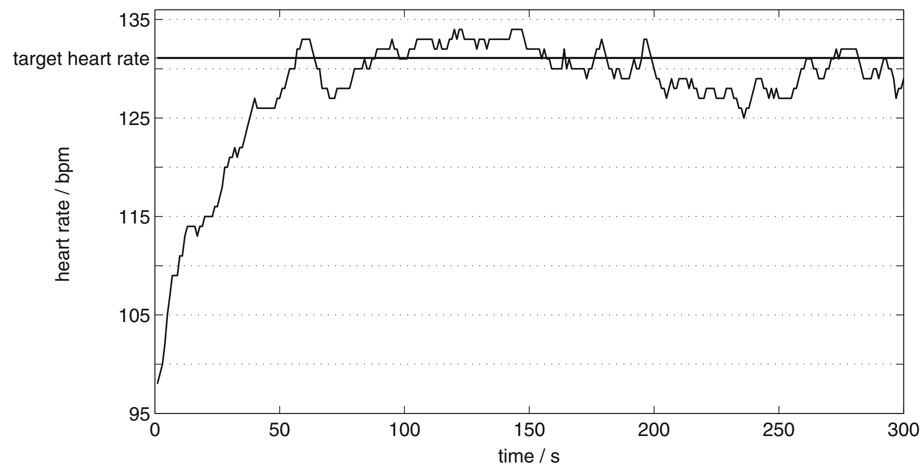

Fig. 8 Course of the subject's heart rate and target heart rate during exercise session with visual feedback

4.6 Evaluation

4.6.1 Heart rate data

Figure 8 shows a typical course of a subject's heart rate during an exercise session. As can be seen, the participant starts from his/her resting heart rate and aims to reach the target heart rate and stay close to the target heart for the duration of the session. For each participant and for every session containing 300 data points (1 data point for every 997 ms, as mentioned earlier), we chose to retain the heart rate data from 100 s till the end of 300 s. This was found to be most convenient to analyze the effects of the feedback methods, as against starting the analysis from the beginning of the exercising session.

All the participants had reached the target heart rate at least once within 100 s and thus, this was considered a relevant starting point for our analysis.

In this way we received 200 valid data points for each session. Please note that the edgy-shaped course of the measured/monitored heart rate is not caused by actions of the subject but by rounding the heart rate to integers and by faster heart rate fluctuations that are not correlated with the subject's effort [10]. These fluctuations cannot be completely removed by the Polar H7's internal nonlinear heart rate filter and are therefore monitored. However, we decided to use the Polar H7's filtered and rounded heart rate data in order to make a fair comparison between state-of-the-art visual heart rate monitoring and our auditory and audiovisual feedback methods.

For each data point, we analyzed the ratio of the absolute difference between actual heart rate and the target heart rate and the target heart rate, as defined by

$$\lambda(t) = \frac{|\mathcal{H}(t) - HR_{target}|}{HR_{target}}, \quad (14)$$

where $\lambda(t)$ is the normalized absolute deviation of the instantaneous heart rate from the target heart rate. Since different participants have different target heart rates, depending on age and resting heart rates, we found this to be a good measure of efficacy of the various methods. We averaged this measure over time for all valid data points (100 till 300 s) in each exercising session and received the arithmetic mean $\bar{\lambda}$.

Furthermore, to find possible bias effects for particular feedback methods, the normalized signed deviation from the target heart rate was calculated as

$$\kappa(t) = \frac{\mathcal{H}(t) - HR_{target}}{HR_{target}}. \quad (15)$$

Analogously to λ, we also calculated the average value for each exercising session for κ and received $\bar{\kappa}$.

In total, $16 \times 6 = 96$ $\bar{\lambda}$ samples and the same amount of data samples for $\bar{\kappa}$ served as basis for the analysis. We analyzed the effect of the feedback method (within-subjects factor with 6 levels) on the dependent variables $\bar{\lambda}$ and $\bar{\kappa}$. Since the data is highly non-normally distributed, a Friedman test was carried out for both $\bar{\lambda}$ and $\bar{\kappa}$ [5].

Furthermore, post-hoc multiple comparison tests for the rank sums of the feedback methods were carried out (Wilcoxon-Nemenyi-McDonald-Thompson method [5, p. 295]) in order to find out which feedback methods had significant effects. For the Friedman test and the post-hoc tests we specified a significance level $\alpha = 5$ %.

We expected that the sonification and visual feedback would have a clear advantage over the no-feedback method of exercising in maintaining a stable heart rate close to the target. We also expected that a bimodal feedback (*V+PM* and *V+HB*) might lead to greater stability and less deviation in the participant's heart rate.

4.6.2 Questionnaires

Numerical values from 1 to 5 were assigned to the 5-point Likert scale (1 ... totally disagree, 5 ... totally agree). Concerning the final question, where the participants had to put the feedback methods in an order according to how they liked them, numbers from 1 to 6 represented the ranks (1 ... best, 6 ... worst). With each question we calculated the median of the responses and performed a Friedman test on the resulting 16 × 6—response matrix. In this single-factor repeated measures analysis, the within subjects factor is the heart rate feedback method and the dependent variable is the subjects' agreement to the respective statement or the rank. We chose this analysis method because the Likert scale items in our questionnaire can not be assumed to be interval scaled, and in the ranking the scale is definitely only an ordinal one [8]. If the Friedman test showed significant effects of the feedback method at $\alpha = 5\ \%$, post-hoc multiple comparison tests (Wilcoxon-Nemenyi-McDonald-Thompson method) were done in order to find out, for which feedback methods the medians were significantly different.

5 Results

5.1 Heart rate data

In Fig. 9 the distribution of all $\bar{\lambda}$ values for the respective feedback methods is displayed.

Performing the Friedman test on $\bar{\lambda}$ as described in 4.6.1, the results presented in Table 2 were found.

As can be seen, the feedback method clearly has a significant effect on $\bar{\lambda}$ at $\alpha = 5\ \%$. However, in a post-hoc multiple comparison test, significant differences at $\alpha = 5\ \%$ could only be shown between the no-feedback method, which resulted in the greatest rank sum/median for $\bar{\lambda}$, and the feedback methods *V*, *PM*, *V+PM* and *V+HB*. The difference between no feedback and the *HB* feedback method was

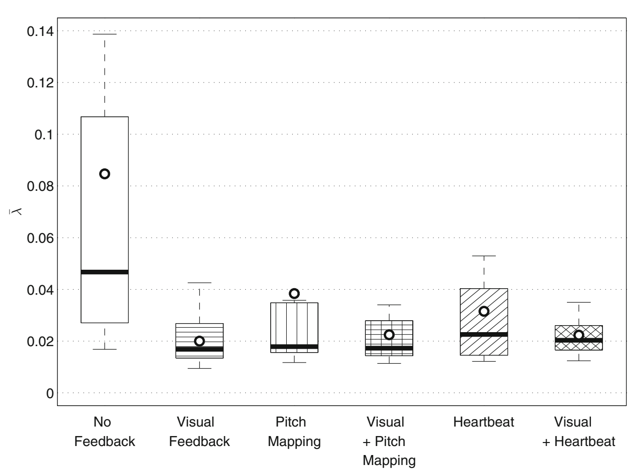

Fig. 9 Box plot showing the distribution of all $\bar{\lambda}$ values for the six feedback methods (the mean of each method is shown as a *black circle*, outliers are not displayed)

Table 2 Friedman test results ($\bar{\lambda}$)

Source of variance	SS	*df*	MS	χ^2	$p(\chi^2)$
Feedback method	110.75	5	22.15	31.64	0.000007
Error	169.25	75	2.257	–	–
Total	280	95	–	–	–

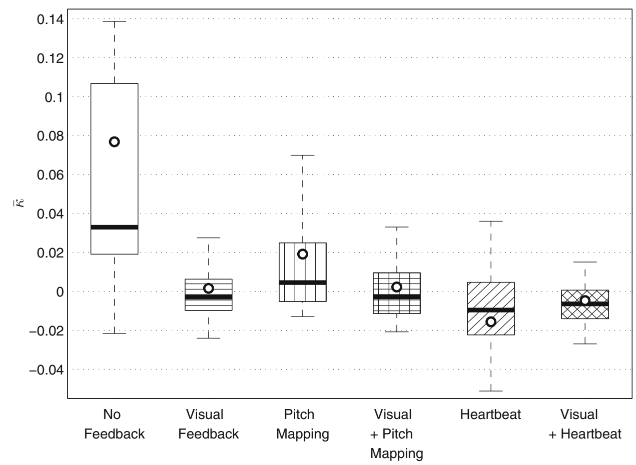

Fig. 10 Box plot showing the distribution of all $\bar{\kappa}$ values for the six feedback methods (the mean of each method is shown as a *black circle*, outliers are not displayed)

Table 3 Friedman test results ($\bar{\kappa}$)

Sourceof variance	SS	*df*	MS	χ^2	$p(\chi^2)$
Feedback method	123	5	24.6	35.14	0.000001
Error	157	75	2.093	–	–
Total	280	95	–	–	–

found to be marginally significant ((corrected) $p = 0.052$). The feedback methods among themselves were not statistically significantly different from each other. Nevertheless, the medians (please refer to thick horizontal bars in Fig. 9) values show tendencies: The median $\bar{\lambda}$ values of the methods *V*, *V+PM* and *V+HB* are very close to each other. This indicates that in this particular experiment, using an auditory feedback in addition to a visual one has no effect or a negligible effect on $\bar{\lambda}$. The median $\bar{\lambda}$ values of the auditory-only feedback methods (*HB*, *PM*) are higher than those of the respective multimodal feedback methods. The median $\bar{\lambda}$ value of the *PM* method is only slightly higher than the median $\bar{\lambda}$ value of the *HB* method. Table 4 (see Sect. 5.3) summarizes the results together with subjective results from the questionnaires.

Analogously, $\bar{\kappa}$ was analyzed. Fig. 10 illustrates the distribution using box plots. The Friedman test on $\bar{\kappa}$ as described in 4.6.1 showed the results presented in Table 3.

A significant effect of the feedback method on $\bar{\kappa}$ was detected at $\alpha = 5\ \%$. We therefore infer that the feedback methods result in different median training intensities, where one or several feedback methods tendentially lead to over- or undershooting the target heart rate.

The post hoc multiple comparison test showed statistically significant differences of the rank sums/medians (please refer to thick horizontal bars in Fig. 10) between the no-feedback method and each of the methods *V*, *V+PM*, *HB* and *V+HB*. The rank sums of the methods *PM* and *HB* were also significantly different. All other pairwise comparisons showed no significant differences. However, the following tendencies can be noticed: The method with the lowest median of $\bar{\kappa}$ is *HB*, where the subjects rather tended to undershoot the target heart rate. Also in the *V+HB* method the median $\bar{\kappa}$ value is rather negative. The median $\bar{\kappa}$ values of the methods *V* and *V+PM* are the closest to zero. A positive median value of $\bar{\kappa}$ is noticed in the methods *PM* and *NF*, here the subjects rather tended to overshoot the target heart rate. The greatest bias is that in the *NF* method, where subjects were drastically overshooting the target heart rate.

5.2 Questionnaire

In this section, the responses to selected statements (see Sect. 4.5) are presented using box plots (Fig. 11). Furthermore, any significant differences found in post-hoc multiple comparison tests as well as tendencies are mentioned.

– *"The mapping of the heart rate to the sound is intuitive."*

We expected the auditory feedback methods to all be considered rather intuitive because of the simplicity of the sonification approaches. As can be seen in Fig. 11, all of the auditory and audiovisual feedback methods were rated intuitive by the participants (except for few outliers). No statistically significant differences between the methods could be detected. ($df_{FeedbackMethod} = 3$, $df_{Error} = 45$, $df_{Total} = 63$, $Friedman's\ \chi^2 = 0.75758$, $p = 0.8596$).

– *"The monitoring helps me with reaching/maintaining my target heart rate."*

Our expectation concerning the helpfulness of the feedback methods was that all the feedback methods (visual, audiovisual and auditory) were well suitable to convey information to the subjects and would therefore be considered helpful. All of the feedback methods were - on average - considered rather helpful. Again, no statistically significant differences were found. ($df_{FeedbackMethod} = 4$, $df_{Error} = 60$, $df_{Total} = 79$, $Friedman's\ \chi^2 = 7.3418$, $p = 0.1189$).

– *"The sound is pleasant."*

Due to the more sophisticated sound design, we expected a supremacy of the heartbeat-based feedback methods over the pitch mapping methods concerning euphony. Fig. 11 shows that the auditory and audiovisual feedback methods were rated moderately pleasant. This indicates that the sound design in the proposed auditory feedback methods can still be improved. The Friedman test showed statistically significant differences between the feedback methods at a $\alpha = 5\ \%$ significance level. ($df_{FeedbackMethod} = 3$, $df_{Error} = 45$, $df_{Total} = 63$, $Friedman's\ \chi^2 = 12.709$, $p = 0.00531$) A post-hoc multiple comparison test shows that the medians of the agreement to this statement are statistically significantly lower ($\alpha = 5\ \%$) in the methods *P* and *V+PM* than in the method *V+HB*.

– *"I would exercise in this way in everyday training."*

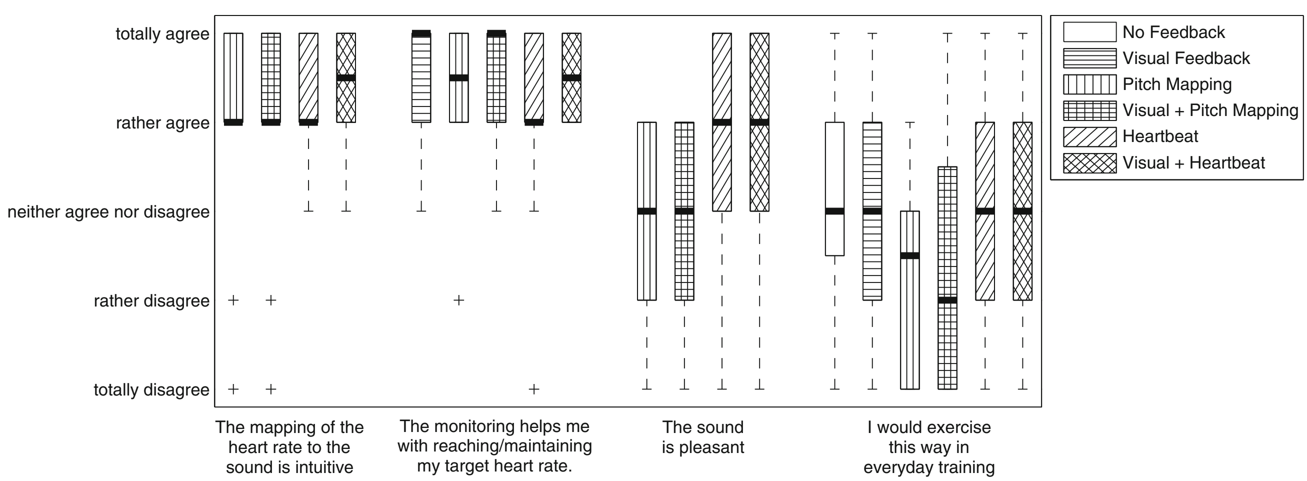

Fig. 11 Box plot showing the subjects' agreements to selected statements on a 5-point Likert scale. *Crosses* represent outliers

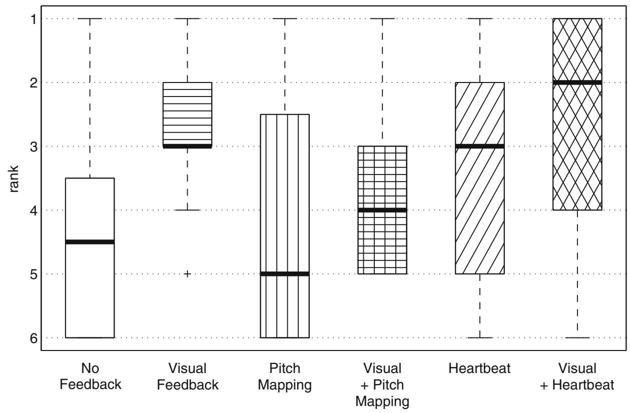

Fig. 12 Box plot showing the distribution of the ranks when the participants were asked to put the feedback methods in an order according to how they liked them

In Fig. 11 it can be seen that for none of the feedback methods a preference over having no feedback at all in everyday training can be shown. Although the Friedman test showed no significant effect, ($df_{FeedbackMethod} = 5$, $df_{Error} = 75$, $df_{Total} = 95$, $Friedman's\ \chi^2 = 7.8097$, $p = 0.167$), tendencies can be noticed, that the "pitch mapping" based methods do not perform as well as the "heartbeat" based methods.

– *Final ranking*

A tendency of preferring the *HB* method over the *PM* method and of prefering the visual and audiovisual methods over the auditory methods can be seen in Fig. 12. The Friedman test showed significant effects of the feedback methods at $\alpha = 5\ \%$ ($df_{FeedbackMethod} = 5$, $df_{Error} = 75$, $df_{Total} = 95$, $Friedman's\ \chi^2 = 12.7500$, $p = 0.0258$). However, the multiple comparison test ($\alpha = 5\ \%$) could not show any statistically significant differences.

5.3 Discussion

Table 4 summarizes the results. From the big difference between the median values of the average normalized absolute deviation in the *NF* and all other methods, we may infer that the feedback process definitely plays a positive role in helping maintain a steady target heart rate and proves our initial assumption that feedback might help athletes train better in certain exercising zones. We had presumed that the sonification methods would significantly reduce the normalized deviation from the target heart rate when used in conjunction with the visual feedback mode, but this does not seem to be the case. In this particular experiment setup, the bimodal methods do not have an advantage over the unimodal visual feedback method. Adding an auditory display to a visual one does not improve the athlete's overview of the heart rate course in a way that enables him/her to maintain a steadier heart rate.

Table 4 Summary of objective and subjective results

Method	$med(\bar{\lambda})$	$med(everyday)$	$med(rank)$
NF	0.0467	"neither agree nor disag."	4.5
V	0.0169	"neither agree nor disag."	3
PM	0.0179	"r. disag."-"neith. a. n. d."	5
V+PM	0.0173	"rather disagree"	4
HB	0.0226	"neither agree nor disag."	3
V+HB	0.0203	"neither agree nor disag."	2

For each method, the median of the averaged deviation from the target heart rate as well as the median of the agreement to the statement "I would exercise in this way in everyday training." and the median of the rank (when the participants were asked to put the methods in an order) is shown (please notice which values have statistically significant difference in the sections above)

As our experimental setup entailed participants working out on a static bicycle, they had the opportunity to visually monitor their heart rate on the iPad in front of them, which might account for the strong performance of the visual feedback methods. We believe that in real world exercising scenarios such as bicycle training or running, where the visual sensory mode is (partially) occupied (concentrating on the road ahead while biking or running), the bimodal methods might provide a strong performance for maintaining a steady heart rate.

A possible reason for the tendential bias in the methods *HB* and *V+HB* that is presented in Sect. 5.1 could be the only approximately (by trial and error) perceptually adjusted amplitude weighting of the high and the low pitched disturbing square tone (see Eq. 10). A possible reason for the tendential bias in the *PM* method could be the effect of the order of two pitches on the feeling of urgency. An ascending note sequence could be perceived more urgent than a descending one. However, this hypothesis could be tested by inverting the order of the fixed tone representing the target heart rate and the varying tone representing the current heart rate.

Concerning the subjective results, we consider the agreement to the statement "I would exercise in this way in everyday training." a good measure of usability. The fact that in this respect the *NF* method performed more or less as well as all of the feedback methods is probably due to the circumstance that none of the test subjects was a professional athlete. While heart rate monitoring is often used in professional endurance training [2], apparently only some non-professional athletes prefer having a monitoring of their heart rate. However, among the feedback methods, the "pitch mapping" based methods do not seem to perform as well as the "heartbeat" based methods concerning this matter. When having simple parameter mapping approaches as in our auditory feedback methods, intuitiveness does not seem to be an issue; Sect. 5.2 shows that all of the feedback methods are perceived intuitive and helpful. A continuous auditory feedback requires a sophisticated sound design in order not to make the feedback annoying. In the "pitch mapping" based methods, sound aesthetics seem to be a problem: some of the participants complained about too "squeaky" sounds or suggested not to use sine tones for this method. The "heartbeat" based feedback methods, which simulate the sound of the heartbeat, appeal more to the participants. The impression of listening to the own heartbeat while exercising seems to be an interesting experience. This also shows in the fact that the *V+HB* method has the best median rank in the final ranking. Thus, we can deduce that when designing an auditory feedback method for heart rate monitoring, it can be useful to have a creative concept that the mapping is based on.

6 Conclusions

We proposed various feedback methods for heart rate monitoring for athletes, including two sonification methods, which both were tested in a unimodal and in an audiovisual context. Under the conditions of experimentation we created, all of the feedback methods performed better than the no-feedback method in maintaining the athlete's heart rate at a given target heart rate. Thus, heart rate information for athletes can aid help athletes maintain their training in certain "zones" more consistently and thus attain more benefits of such informed training. In further research, we would like to develop a standardized evaluation method for the kind of experiments as presented in this article, which has to be considered an interdisciplinary task. Further experiments have to be done with more participants in order to be able to deduce more conclusions. Furthermore, the same feedback methods have to be tested in a different setup, where the sensory input of vision is well occupied, to see whether sonification methods outperform visual methods.

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