

## REAL-TIME HEART RATE SONIFICATION FOR ATHLETES

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### ABSTRACT

In this paper, we describe a sonification system that delivers instantaneous heart rate information to an athlete. The sonification system uses a textitPolar H7 heart rate sensor to monitor the heart rate of the user. We describe the techniques used for the processing of the captured heart rate data, its sonification and the relevance of the feedback methods via both a subjective and objective analysis. Our tests prove the strength of having a method for the sonification of instantaneous heart rate. Our testing procedure also serves as a pointer for evaluation of the efficacy of sonification methods in general.

### 1. INTRODUCTION

Instantaneous feedback to an athlete has been proven to improve training and performance throughput [1]. One such feedback is the heart rate monitor which measures the exertion of an athlete's heart. Since the introduction of wireless heart rate monitors, professional and amateur athletes alike have used them with great success to optimize their training regimen. A heart rate monitor provides real-time information to athletes, which, if evaluated and used correctly, may be helpful in fine tuning aspects of a workout, such as training intensity, training time, recovery time, etc. Furthermore, the resting heart rate of an athlete may be used as a measure of fitness and efficacy of training. Thus, having such a real-time heart rate information as a feedback may help an athlete to train better, ensuring lesser injuries, better performance and shorter recovery times. Burke in his work [2], talks about the advantages of using heart rate monitoring in sports training using scientific methods. To develop efficient heart rate monitoring sonification systems, it is crucial to know the applications and the limitations of such systems.

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 smartphone or a watch. The phone or watch can be used as a visual aid for understanding the heart rate information. One of the features in most of these applications is a real-time visual feedback 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, biking), thus preventing an athlete from frequently looking at his visual feedback display.

A useful mode of giving feedback to the athlete in such a scenario is using sonification of the heart rate [3]. This way, an athlete listens to the sonified feedback, thus freeing his cognitive load of having to visually monitor the feedback periodically. Another aspect of sonification for feedback is to intelligently sonify other aspects of training such as training intensity, trend of the heart rate, duration of a particular stage of training etc. Thus, multiple dimensions of a training session could be sonified in a single stream. We decided to design a sonification of instantaneous heart rate with various add ons to test the efficacy of training in a particular zone.

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 [4]. Godbout et al. [5] 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 of 2013. Schaffert et al. [6] 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 in an increase in mean velocity of the boat. This method was tested on professional rowers from the German Rowing Association.

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

### 2. SONIFICATION FOR REAL-TIME HEART RATE MONITORING

Although current heart rate monitoring systems exist which give auditory feedback to the user using discrete time auditory clues, they give continuous feedback only visually [4]. As previously mentioned, this visual feedback is not useful when an athlete is running or biking.

In this paper we propose a continuous sonification of heart



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rate in order to provide the user with instantaneous feedback on their heart rate, performance level and effort required to reach a target heart rate and maintain it for a sustained period of time. We also intend to use this method as a platform to propose future sonifications which may indicate trends, deviation from a target heart rate and allow the user to follow a performance curve etc.

## 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 chest and starts his activity. The sensor has a wireless connection to a smartphone or tablet. The analysis of the heart rate information and sonification is performed in the tablet. The athlete gets auditory feedback about his instantaneous heart rate through headphones and visual feedback via the tablet display. The athlete may use the sonified feedback to control his 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 his effort accordingly.

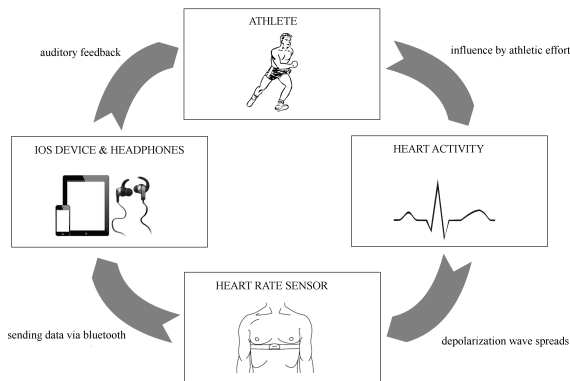


Figure 1: Block diagram for the proposed system

## 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 filtered R-R interval information (an integer heart rate value in BPM) once every 997ms.

We used an *Apple 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 in the sonification scheme with *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 sonified audio. We used *Monster iSport Victory* sports earphones for delivering the sound to an athlete as he exercised on a sports bike. More details about the testing modalities are described in Section 4.



Figure 2: Polar H7 sensor

## 2.3. 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 ( $A$ ) [4].

To determine an athlete's resting heart rate, his 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 is best estimated 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 [7],

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

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 and thus changes with time. 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 [8], 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 the  $HR_{min}$  and  $HR_{max}$  based on training intensity  $\mathcal{T}$  (in %) as,

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

In the  $\%HR_{max}$  method [9], the target heart rate is calculated as a percentage of the  $HR_{max}$  without taking the resting heart rate into consideration as,

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

As given in Table 1, training at various intensities has differing benefits. The table also gives the durations for which the training

is usually carried out and the heart rate to be maintained (in percent of  $HR_{max}$ ) in order to experience their benefits. We have chosen to use the Karvonen method for our analysis, as explained in Section 4.3 with a training intensity of 0.5.

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

Table 1: Sporting zones, as obtained from the Polar sensor website.

### 3. SONIFICATION MODELS

In our system we try to find a balance between continuous and discrete auditory feedback in order not to overload the athlete’s auditory sense while being pleasant and intuitive. We adopt a parameter mapping approach which continuously maps the instantaneous heart rate to a sonification parameter. 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 and enables the athlete to determine their instantaneous heart rate ( $\mathcal{H}(t)$ , where  $t$  is the time parameter.  $t$  is omitted from the equations involving  $\mathcal{H}(t)$  for ease of reading) and the percentage intensity at which they are exercising. 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 the  $HR_{min}$  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 time duration of a periodically repeating note can be used 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  $\mathcal{H}$  to a pitch or duty cycle, but in order to create a constant anchor of  $HR_{target}$  for the athlete, we would need to create a second auditory stream. As a modification, we created an approach that maps the difference between  $\mathcal{H}$  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 when the athlete’s heart rate differs from his target heart rate. Once the athlete reaches his target heart rate, the sound stream becomes complete.

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

#### 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 are used to represent the most recent heart rate value. Our first approach was to display the  $\mathcal{H}$  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 for a user. 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  $\mathcal{H}$  and the second corresponding to  $HR_{target}$ . Thus, the athlete has to adjust the first note to match the second note and then he would be exercising at his target heart rate. This method too had a small problem that small changes in pitch were difficult to distinguish for most people. Thus, we quantized the pitches so that an athlete could clearly hear whether he 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 the Fig. 3. As seen, the signal is periodic with a period of 2650ms.

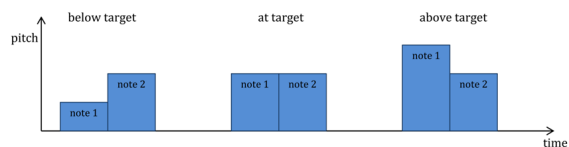


Figure 3: Schematic diagram of the pitch mapping sonification method

The audio signal can be expressed as,

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

where  $\epsilon(t)$  is an envelope function defined as an ASR (Attack Sustain Release) signal and  $f_1(\mathcal{H})$ ,  $f_2(\mathcal{H})$  are frequencies dependent

on the current heart rate. The envelope function is defined as,

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

where  $\tau = \text{rand}(20ms, 40ms)$  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  $f_1(\mathcal{H})$  which maps the current heart rate  $\mathcal{H}$  to a pitch is given as,

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

while the quantity  $f_2(\mathcal{H})$  is a constant, given as,

$$f_2(\mathcal{H}) = 771Hz. \quad (8)$$

### 3.2. Heart beat events with loudness mapping

In this approach, we sonified the instantaneous heart rate  $\mathcal{H}$  using a simple model for the heart beat. To this heart beat, we added a disturbance signal of a differing loudness depending on whether  $\mathcal{H}$  was below or above  $HR_{target}$ . When  $\mathcal{H}$  was below  $HR_{target}$ , a low pitched tone was added whose amplitude level was proportional to the difference between the target heart rate and the current heart rate. The same approach was followed when  $\mathcal{H}$  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 heart beat at his target heart rate and the disturbing signal shall act as a feedback to aid him to either increase or decrease his 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 disturbing sound model, we used square waves of two fixed frequencies, a low pitch used for the condition  $\mathcal{H} < HR_{target}$  and a high pitch for  $\mathcal{H} > HR_{target}$ . This sonification method is presented in Fig. 4.

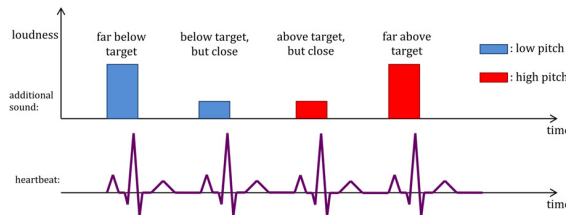


Figure 4: Schematic diagram of the heartbeat events with loudness mapping sonification method

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

$$x(t) = h(t) + d(t, \mathcal{H}), \quad (9)$$

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

$$h(t) = \mathcal{L}(e(t) \cdot [n(t) + 0.5 \cdot \sin(2\pi \cdot 60 \cdot t)]), \quad (10)$$

where  $\mathcal{L}$  is a low-pass operation with a second order resonant IIR filter of cutoff frequency of  $200Hz$  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.

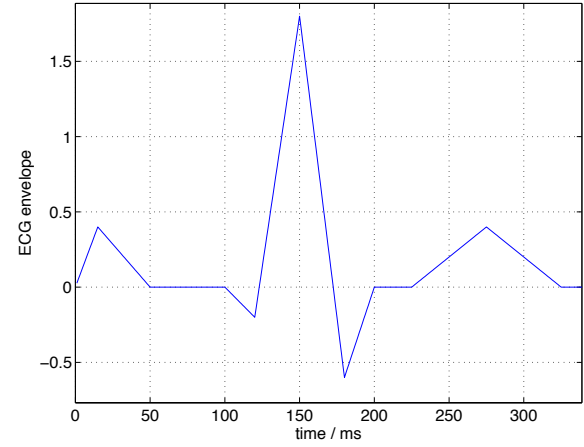


Figure 5: Envelope of the heart beat sound

The disturbing square wave sound is calculated as follows,

$$d(t, \mathcal{H}) = [l(\mathcal{H}) \cdot s(t, f = 70Hz) + g(\mathcal{H}) \cdot s(t, f = 2000Hz)] \cdot e_s(t), \quad (11)$$

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

$$e_s(t) = \begin{cases} \frac{t}{\frac{8}{60}ms} & , 0 < t \leq 5ms \\ \frac{\frac{8}{60}ms - t}{300ms} & , 5ms < t \leq 305ms \\ 0 & , \text{elsewhere.} \end{cases} \quad (12)$$

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

$$l(\mathcal{H}) = \begin{cases} \min\left(1, 10 \frac{-26 + 130 \cdot \left(1 - \frac{\mathcal{H} - HR_{min}}{HR_{target} - HR_{min}}\right)}{20}\right) & , \mathcal{H} < HR_{target} \\ 0 & , \mathcal{H} \geq HR_{target}. \end{cases} \quad (13)$$

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

$$g(\mathcal{H}) = \begin{cases} 0 & , \mathcal{H} < HR_{target} \\ \min\left(1, 10 \frac{-26 + 130 \cdot \left(1 - \frac{\mathcal{H} - HR_{min}}{HR_{target} - HR_{min}}\right)}{20}\right) & , \mathcal{H} \geq HR_{target}. \end{cases} \quad (14)$$

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 is above or

below a target heart rate. Also, the level of the square wave being played as a disturbance to the synthesized heart beat 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 shall describe the experiments in detail in this section.

##### 4.1. Experimental Setup

To test our feedback methods, we used a Spin Racer Plus SP-SRP-2802 spin bicycle in a gymnasium in the premises of the Fraunhofer IIS. We used a setup as shown in Fig. 6. Participants had to workout 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.

##### 4.2. Participant Demographics

16 participants, all employees of the 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 mean age of participants was 28.6. Of the participants 3 were female and the rest were male.

##### 4.3. Experimental Procedure

Each participant was given up to 5 minutes 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 integer heart rate value over a 30 second period. The subject then exercised on the spin cycle for a five minute period with the help of one of the many methods of feedback. Our aim was to compare the deviation from the target heart rate of an athlete in such a scenario. The subject exercised for a 5 minute period with a particular type of feedback followed by a cooling down period of 5 minutes, 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 feedback methods was randomised for every participant in order to avoid the systematic bias error caused by learning or tiring effects. The entire testing procedure thus, consisted for 6 sessions of 5 minute exercises followed by 5 minute cooling down period. The cooling down period was also used for

filling up a questionnaire on the just concluded exercise session. The cooling down period was necessary to lower the heart rates of the participants before another exercise session. Before an exercising session the subject was briefed about the feedback method and audio examples were presented (in case of sonification methods). Furthermore to get an intuitive understanding of the sonification methods, they could do training sessions for 2 minutes for the feedback methods that involved auditory feedback. The whole test took a total of around 60 minutes (including the cooling down periods). The tests were manually monitored by the first author.



Figure 6: Experimental setup

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.



Figure 7: iPad with the app

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 calculated the subject’s target heart rate using Karvonen’s method [8] with a training intensity of 0.5.

#### 4.4. Questionnaire for the feedback methods

Between two exercise 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 [10] 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 exercise sessions or the testing methodology.

#### 4.5. Evaluation

We evaluated the 6 methods described in 4.3 using a normalized deviation from the target heart rate as a measure of efficacy. We inspected the mean values of the deviation for all the methods using an analysis of variance (ANOVA) framework [11]. 95% confidence intervals were calculated using the bootstrap method [12]. We expected that the sonification and visual feedback would have a clear advantage over the no-feedback mode of exercising in maintaining a stable heart rate close to the target. We also expected that a bimodal feedback (i.e V+PM and V+HB) might lead to greater stability and lesser deviation in the participant’s heart rate. We had also requested the participants to rank the 6 methods on a perceptual sense, with a rank of 1 implying the best and easiest method to use and rank of 6 implying the worst. We found the mean rankings for the 6 methods using the rankings provided by the participants as a measure of usefulness of the feedback method.

## 5. RESULTS

Figure 8 shows a plot of the heart rate for a participant comparing it with the target heart rate for two methods of feedback. 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 approximately 300 data points (1 data point every 997ms, as mentioned earlier), we chose to retain the heart rate data from  $t = 100$  seconds till the end of the session ( $t = 300$  seconds). This was found to be most convenient to analyze the effects of the feedback methods, as against starting analysis from the beginning of the testing session. All the participants had reached the target heart rate at least once within the first 100 seconds and thus, this was considered a relevant starting point for our analysis.

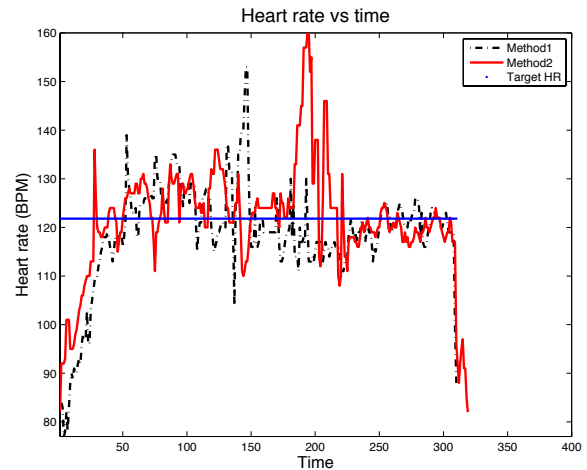


Figure 8: Heart rate (BPM) vs time (seconds)

To analyze the various methods proposed in the previous section, we performed a 1-way ANOVA test on the 6 methods independent of the participants. We analyzed the ratio of the absolute difference between actual heart rate and target heart rate and the target heart rate, as defined by,

$$\lambda(t) = \frac{\text{abs}(\mathcal{H}(t) - HR_{\text{target}})}{HR_{\text{target}}}, \quad (15)$$

where  $\lambda(t)$  is the normalized absolute deviation of the instantaneous heart rate from the target heart rate. Note that we have reintroduced the  $t$  parameter in  $\mathcal{H}(t)$  to indicate that it is a time dependent quantity. We had dropped it in our previous equations only for ease of representation. 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. Table 2 shows the means and the 95% confidence intervals for  $\lambda(t)$  and also the mean rankings as averaged over 16 participants. As can be seen, the mean rank for the V+HB method appears to be the best one perceptually for the users and the NF method has the worst rating. We can thus deduce that having a feedback for training was considered useful by the participants. Also, the usefulness and ease as perceived by the participants is reflected roughly in the mean deviation column. The NF method has the highest mean deviation while the V method has the lowest.

We also performed posthoc tests to ascertain whether the differences in means were statistically significant. We found that there is no statistically significant difference between the methods V, V+PM and V+HB, while the other methods have a statistically significant difference in their means. The mean ranks of V

Method	Mean deviation	C.I	Mean rank
NF	0.0847	[0.0816 0.0879]	4.4375
V	0.0199	[0.0193 0.0206]	2.8750
PM	0.0384	[0.0366 0.0402]	4.2500
HB	0.0315	[0.0304 0.0327]	3.2500
V+PM	0.0224	[0.0215 0.0233]	3.6250
V+HB	0.0223	[0.0216 0.0230]	2.5625

Table 2: Mean normalized deviation and the corresponding 95% confidence intervals. The mean ranking as scored by participants is also shown.

and V+HB are very close, while the V+PM method is not well received even though it seems to aid in low deviation from the target heart rate. Also, amongst the sonification only methods, the HB scheme performed way better than the PM method. The mean rank also concurs on this point. Furthermore, the NF method performs worst in both the objective measure and the subjective ranking aspects. Fig. 9 shows the medians, the means and the 25<sup>th</sup> and 75<sup>th</sup> percentile values of all the 6 methods.

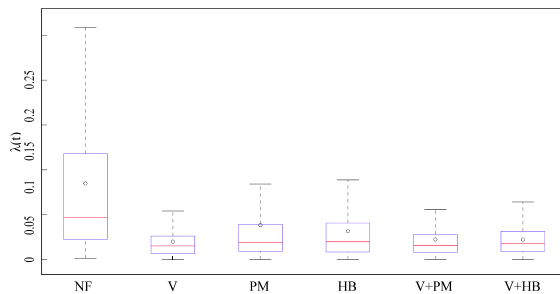


Figure 9: Boxplot showing the medians for various methods along with their 25<sup>th</sup> and 75<sup>th</sup> percentile values. The mean values for each method are shown in black circles.

From the discussion above, we may infer that the feedback process definitely plays a positive role in helping maintain a steady target heart rate. We had presumed that the sonification methods would significantly reduce the normalized deviation, when used in conjunction with the visual feedback mode, but this doesn't seem to be the case. As our experimental setup entailed participants working out on a static bicycle, they had the opportunity to visually monitor the iPad in front of them and this 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 occupied (having to concentrate on the road ahead while biking or running) the sonification methods might provide a strong performance for maintaining a steady heart rate. The sonification method HB, which simulates the sound of the heart beat, seems to aid the participant very well. Also the ease of use and overall likeability of this method is reflected in its mean rank score. A sonification method like this may perform well in the scenario described above. On the whole, all feedback methods performed better than the NF method, thus proving our initial assumption that feedback might help athletes train better in certain exercise zones.

## 6. CONCLUSIONS

We proposed various feedback methods for heart rate monitoring for athletes. We proposed two sonification methods to monitor heart rates. Under the conditions of experimentation we proposed, we found that the visual feedback methods aided with sonification performed best in maintaining steady target heart rates. Also, the sonification only methods performed better than the no-feedback mode. Thus, heart rate information for athletes can help them maintain their training in certain "zones" more consistently and thus attain better benefits of such informed training. We would like to test the same algorithms 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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