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HeartBeat: Tactile Support for Keeping a Target Heart Rate

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Abstract

In cardiac rehabilitation, physical activity is essential, but the intensity of exertion as defined by the heart rate should be kept within specific limits. A heart rate monitor helps the user maintain the target range of physical exertion for maximum benefit. According to experts, visual heart rate display are often distracting and uncomfortable. In this paper, we present the results of a less intrusive approach where heart rate zones are encoded with continuous vibro-tactile feedback. In a participatory design study, we obtained designs for tactile heart rate displays, and in a user study with 16 participants we evaluated one design in comparison to a common design. In a second study with 20 participants, we showed that users are able to assess and maintain their optimal heart rate significantly better using our design.

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1. Introduction

Cardiovascular diseases are responsible for nearly 25 percent of all deaths in the world [1]. For patients who suffer from a cardiovascular disease, many of whom have already had a heart attack, cardiac rehabilitation is essential to recovery. Cardiac rehabilitation, including controlled physical activity, has been shown to significantly reduce all-cause mortality and cardiac mortality and has a positive effect on physiological parameters [2–5].

Physical activity is a main element of cardiac rehabilitation as it improves the overall constitution of the patient while strengthening the heart. A minimum of 30 minutes of moderate-intensity physical activity per day reduces the coronary risk factors and increases the patient's well being [6]. During the activity, however, patients may find it hard to maintain the optimal intensity of exertion, especially untrained patients not used to their new physical condition.

The heart rate is a key indicator for intensity of exertion. During cardiac rehabilitation, patients learn about the importance of the heart rate and learn the optimal target range of their own heart rate during physical activity. These limits can be determined using the maximum heart rate which is normally determined during the cardiac rehabilitation. The optimal intensity is then defined by an upper and lower limit for the heart rate during physical activity. During the training, the patients then try to keep their heart rate within these limits.

Today, patients, athletes, and others who want to monitor their heart rate often use a heart rate wristwatch. These watches have the drawback of requiring visual monitoring for the information, which can be uncomfortable and distracting, taking too much of the user's attention from the physical activity itself. Some variants of the wristwatch can also inform the wearer through tactile or audible alarms if previously entered limits are reached. The problem with these variants is that the alarms are often the same for both the upper and lower limits. These simple vibro-tactile notifications fail to address the problem, because they still require users to look at a display to classify the information. Further, according to experts, user seeking to avoid frequent alarms set the upper and lower limits wrong, making them higher and lower than the optimal range. These wrong limits may then be learned by the user, who looks at the watch to read the concrete

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Figure 1. Whilerunning the user of a visual heart rate display mustshift attentionaway fromthe actual activity to monitothe heart rate.

values. Using audio cues can resolve these issues, but audio cues may be unwanted by the runner or even be dangerous when a physical activity like running is performed in public places with traffic [7].

To address these issues, we developed a method not only to encode hard limits with tactile feedback, but also to use a user-designed more detailed tactile feedback to convey multiple borders of different heart rate zones. In contrast to existing systems, this feedback allows the assessment of the heart rate without a distracting visual display. Further, with a tactile-only display which not just shows the outer limits, we avoid the alarm character of the tactile signals and keep the user constantly aware of the heart rate. Users in our study evaluated and created several patterns, and we compared one of these patterns against the tactile feedback given by a common heart rate watch. Our results show that users were able to assess and keep their optimal heart rate significantly better with the new design.

2. Related Work

The encoding of abstract messages using tactile feedback was described by Brewster et al. [8]. These abstract messages are called *Tactons*. Tactons can be used to display information without demanding other senses like sight and hearing. Tactile abstract messages like Tactons have been proven to be able to encode several types of information [9], e.g. progress information [10] and navigational tasks [11, 12]. Lee et al. [13] evaluated the perception of tactile displays worn on the wrist. They showed a high discrimination rate of patterns up to 99 percent and found that intensity is the most difficult parameter to distinguish, with temporal patterns being the easiest. Thus, in our work we decided to focus on temporal patterns. These papers showed us that vibro-tactile feedback at the wrist is a good way to communicate information without distracting the user.

The related work showed us that the interest of users in tactile representation techniques for their heart rate is high. Two approaches exist that use displaying the heartbeat to create intimacy between two people. Lotan et al. [14] proposed a device for augmenting intimate or meditative moments between people at a distance. The device has an outline of hands on the surface where the users can place their hands. The device is then able to reflect the user's heartbeat or even to simultaneously use two vibration motors to show the heartbeat of the local user and a user of another device. Werner et al. [15] created a similar approach in which two partners wear rings that, with the help of a small vibration motor, enable the wearer to feel the partner's heartbeat. Most participants liked the vibrations, which felt very similar to a known heartbeat. Hoinkins [16] presented with *Herzfassen* a bowl filled with water, which visualized the heartbeat using vibrations and the resulting patterns in the water surface. People experienced the visualisation of the heartbeat as interesting and tried to influence their heart rate by doing e.g. push-ups or knee-bends.

Buttussi et al. [17] created a mobile device called MOPET for supporting the outdoor training. The device supports the navigation by providing audio and visual navigation instructions, supports jogging by visualising speed and heart rate and by providing motivational and safety advice, and supports exercises by giving advice. The device is designed to support training and workouts but is not designed to support patients in cardiac rehabilitation, who have special needs.

Our prior work was the direct encoding of the heart rate in a project called HapticPulse [18]. Every heartbeat measured by a chest belt was represented by a vibration impulse of a connected smartphone. Users were able to feel their heart rate with an accuracy of 10 beats per minute and reported a raised awareness about their heart. One problem revealed was the distraction. The heartbeat and therefore the tactile feedback sometimes interfered with the rhythm of walking or running, which disturbed the users. This approach showed us that the tactile encoding of information about the heart rate is effective and liked by users but has to be designed to not interfere with the rhythm of running or walking when used during training.

There are also commercial products that support the user in measuring the heart rate and in keeping it in defined borders for training purposes. One example is the *Garmin Forerunner 610*[1]. In addition to acoustic signals when the heart rate exceeds certain limits, the Garmin Forerunner 610 can also give tactile feedback in the form of a vibration impulse. These commercial products are still very limited. They can provide an alarm-based feedback when limits are reached but require the user to look at the display to assess the heart rate and the reason for the alarm. Consequently, unobtrusive training is not possible. In contrast, we wanted to create a vibro-tactile feedback that can help users stay within certain limits without looking at a visual display and keep users as informed about their heart rate as they want. Apps like *Runkeeper*[2] and *Runtastic*[3] can track a whole workout and also include heart rate recording, so the users can learn about their heart rate during physical activities. Both of these devices can track a workout and enable users to reflect on their performance, but they cannot help the user train in a healthy way. These apps also allow the use of audio feedback that can inform users about distance and speed, as well as the heart rate, which we target in our work. In contrast to that, in our work, we focus on the use of tactile feedback on the wrist. Tactile feedback can be an extension for audio feedback, but also a safe replacement, because it allows users to keep the ears free during physical activity performed outside.

3. Context of Use

To understand the problems and needs of patients when using a heart rate monitor, we conducted a semi-structured interview with two trainers from a clinic and rehabilitation centre for cardiac diseases. The leading questions for the interview were:

- How are patients informed about keeping their designated heart rate?
- Are heart rate watches used for the training?
- How are patients supported in keeping their designated heart rate?
- How would you imagine a heart rate watch especially for your patients?

The following interview results revealed three main findings, which are described below in detail and which we used as the basis for our approach:

1. The heart rate should be kept between 60 to 80 percent of the maximum heart rate. The trainers reported that patients generally spend three weeks in rehabilitation. During this time, patients learn to observe and understand their heart rate. The optimal heart rate range during training is 60 to 80 percent of the maximum heart rate, and patients learn that they should keep their heart rate in this range while being physically active. The maximum heart rate is determined during rehabilitation and conveyed to the patients.

2. Information about reaching the limits should not have an alarm character. Depending on the therapy, the heart rate is measured in different ways. It is measured either by a training device like an ergometer, by the patient her-/himself during group training, or using a heart rate watch during outdoor training. If heart rate watches are used, they are set up to give a signal when the training heart rate strongly exceeds the 80 percent limit. The alarm is not set to the 80 percent limit itself to avoid alarms, which could stress the patient. According to the experts, a new approach should avoid using alarms. Thus, a device should not only warn the user when the outer limits of the acceptable heart rate range are reached, but give hints earlier.

3. The display should be non-visual to avoid distraction. Some patients, especially anxious patients, tend to look at a visual display very often. This can be dangerous if the distraction is too high and the patient becomes unaware of the environment. The patient could, for example, fall and get hurt. Therefore, it would be useful if patients had a non-visual display of their heart rate so as not to draw away their attention from their surroundings.

4. Approach

Our approach to address these issues revealed in the expert interview was not only to use two limits for the heart rate, but also to find, with the help of users, a more complex encoding. Thus, we conducted two user studies. The first was a participatory design study to find which information users would like to get during physical activity, and when and how they wanted to get that information. The expert interview showed that a heart rate display should avoid the visual modality to allow users to concentrate on the activity rather than the heart rate display. As reported in the related work section, tactile feedback has been shown to be less distracting. Thus, we limited the design space to tactile feedback. In the study, we let users design a tactile heart rate display themselves using our given hardware. To evaluate our approach in the field, we did a second study preceded by a pilot study. We derived two different vibration patterns from the designs collected in the first study. In the short pilot study, we chose one of the two designs for further evaluation. Then we tested the use of the best pattern from the pilot study during physical activity and compared it to the pattern used by an existing heart rate monitor.

[1] http://sites.garmin.com/forerunner610/?lang=en
[2] http://runkeeper.com
[3] http://runtastic.com

5. Participatory Design Study

To collect a basic set of user ideas about how a vibro-tactile feedback of a heart rate monitor should look work, we did a participatory design study. The study revealed five different design types, two major designs that were designed by most of the participants and three minor designs. The study was approved by a local ethics committee.

5.1. Appaatus

This study was designed as lab study. A lab study allowed also older users and users with a heart disease to participate. These users are an important target group for a heart rate monitor, but may not want to or should not participate in a study with physical activity. As shown in the literature [13], the wrist is a good position for a wearable tactile display. Thus, we decided to use a Sony SmartWatch[4], which can be worn like a normal watch and is able to give vibro-tactile feedback. For controlling the vibration, we created a simple app, running on a Nexus 7 tablet. This app was designed to be used by the experimenter, not by the users themselves. The app allowed us to enter several rhythms, by entering a sequence of vibration impulse lengths and pauses in between. Thus, our design space was intentionally limited to the these two parameters to allow the creation of temporal patterns, which the related work had shown the be the most distinguishable.

5.2. Participants

We conducted the study with 16 participants (7f/9m). The age ranged from 26 to 79 years. The mean age was 51 years (SD: 12 years). The participants were not paid for their participation.

5.3. Design

The goal of this study was to collect design ideas from users, find similarities, and derive a smaller subset of vibration patterns for further evaluation. To clarify the background of the participants, the study started with a short questionnaire about age, sex, knowledge, experience about the heart rate, and the use of heart rate monitors. For this, we used eight questions/statements:

Question/Statement	Scale
I'm physical active.	5-point Likert
I'm able to assess my heart rate.	5-point Likert
I do exercise regularly.	Yes/No
... if yes, how often per week?	Numerical value
I already used a heart rate monitor.	Yes/No
I know about the the different heart rate zones (anaerobic zone, aerobic zone, ...).	Yes/No
I know my personal optimal training heart rate.	Yes/No
I'm experienced with vibro-tactile feedback.	Yes/No

The designing itself was done by the users verbally while wearing the SmartWatch. Ideas for vibration patterns could instantly be tested by entering the pattern in the app described above, which played back the vibration pattern on the SmartWatch. The app was operated by the experimenter to allow participants to focus on the design part instead of the usage of the application.

During the design, concrete heart rate values for the optimal heart rate and the outer limits were only used if the participant demanded it to support her/his understanding of the thematic. We informed the participants that these values are very different among humans. Thus, also the width between lower and higher limit can differ. When we used limits in the design, we used 130 beats per minute as optimal heart rate and 110 and 150 beats per minute as limits.

5.4. Procedure

At the start we met the user at previously communicated locations. Often, the experimenter visited them at their home. The study then began in a quiet room with only the participant and the experimenter present. The experimenter explained the study goal and the procedure to the participant and answered occurring questions. After the participant had no more questions, she/he signed the informed consent and the actual study started. The experimenter explained what the optimal heart rate for training means and that users need to stay within certain limits to reach specific goals, like optimised fat burning or even to do exercises safely in case of a heart disease. The participant was then asked what feedback she/he thinks she/he would need to stay within these limits. If the participants did not know how to start, the experimenter helped with simple examples like giving a simple signal exactly at these limits, or encode the leaving and entering of the optimal zone differently. The participant then explained what information is important for her/him and tried to express how a possible feedback could feel like. Often,

[4] http://www.sonymobile.com/us/products/accessories/smartwatch/

Description	Impulse length	Pause length
Very short	$< 100ms$	$< 100ms$
Short	$100 - 500ms$	$100 - 600ms$
Long	$500 - 1000ms$	$600 - 5000ms$
Very long	$> 1000ms$	$> 10seconds$ generally 1 - 2 minutes

Table 1. Vibration impulseand pause lengths users described duringthe study

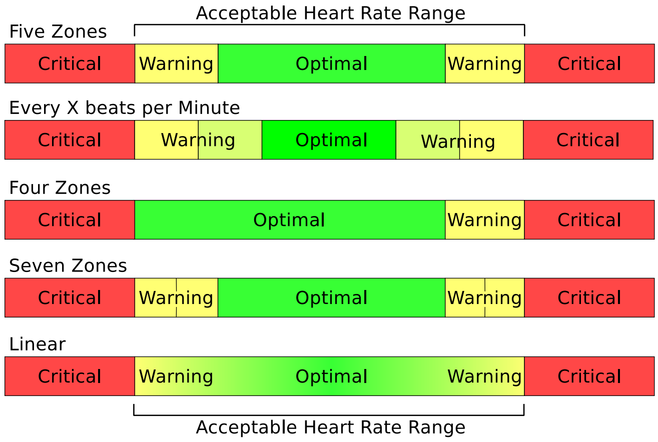

Figure 2. Overviewof the di˙erent design types

the participants needed to define different terms like *very short*, *short*, *long*, or *very long* to express their ideas of a vibration pattern. This was done with the help of the experimenter, starting different vibration lengths and rhythms on the SmartWatch. Then the participants designed different vibration patterns for their information they liked to be encoded. In the end, the experimenter made sure that every decision and the reason was correctly noted by explaining the whole design back to the participant. We thanked the participant for her/his participation and ended the study.

6. Results

The ratings on the 5-point Likert scale were mapped to numerical values. A value of 1 represented *Strongly Disagree*, a value of 5 represented *Strongly Agree*. The questionnaire showed the following results: The statement "I am physically active" received a median rating of 3.0 (Min: 1.0, Max: 5.0, 1st Qu.: 2.75, 3rd Qu.: 3.0). The statement "I am able to assess my heart rate" received a median rating of 2.0 (Min: 1.0, Max: 4.0, 1st Qu.: 1.0, 3rd Qu.: 3.25). Seven participants reported exercising regularly. The median of the frequency of the exercises was 2.0 (Min: 2.0, Max: 4.0, 1st Qu.: 2.0, 3rd Qu.: 2.5) times per week. Five participants had used a heart rate monitor before, six knew about heart rate zones and their effect on the training, only three knew their optimal heart rate for the training, and four had already used some kind of vibro-tactile feedback before.

During the study, most participants did not communicate their ideas for the length of the vibration impulses or pauses with concrete numerical values. Generally, the terms *very short*, *short*, *long*, and *very long* were used. What these values meant for a participant was tested experimentally with the help of the experimenter, who adjusted the lengths until the participant was satisfied. The approximate lengths meant by these terms are listed in *Table 1*. For pauses, sometimes instead of *long* and *short* the terms *slow* and *fast* were used. Few users asked to vary the *intensity* of the vibration itself, which was not possible with the SmartWatch. Instead, they used generally longer or more often occurring vibration impulses to intensify the sensation.

The participatory design study revealed five different types of designs:

Five Zones This design type consists of five heart rate zones. An optimal zone, upper and lower warning zones, and upper and lower critical zones.

Every X beats per minute This design type has a different zone every *X* beats per minute. Thus, it defines a new vibro-tactile pattern for each in-/decrease of the heart rate of X beats per minute.

Four Zones This design type is similar to the *Five Zones* design, but does not use a lower warning zone.

Seven Zones This design type is also similar to the *Five Zones* design, but has four instead of two warning zones.

Linear This design type uses a linear representation of the heart rate. Only critical zones remain.

The most frequent types of designs were the *Five Zones* design and the *Every X beats per minutes* design, which are quite similar, as we describe later. Both were proposed by six users each. Thus, only four participants created other design types: *Four Zones* (2), *Seven Zones* (1) and *Linear* (1). The design types are visualized in *Figure 2*. In the following, we describe the created designs in detail.

6.1. Five Zones

The *Five Zones* design consists of one optimal zone, two warning zones, and two critical zones. The optimal heart rate is located directly in the centre of the optimal zone. The limits of the warning zones are located directly at the average between the optimal heart rate and the minimum and maximum acceptable heart rate. For example, if the optimal heart rate is 130 and the acceptable limits are 110 and 150, the limits for the warning zones would be 120 and 140.

The participants created this design to keep the number of different vibration patterns low and to keep the ability to create easily distinguishable patterns. Especially male participants showed the effort to always keep the feedback for the related zones (upper and lower warning zones, upper and lower critical zones) also related and change only one parameter like impulse length, pause length, or repetition count, while keeping the others.

Optimal zone: Only one participant wished for no feedback in the optimal zone. Another one only wished for one long signal of about one second length, when the optimal zone is reached, but no recurring feedback. The four other participants who created a *Five Zones* design wanted to have a recurring signal, but the opinion about the pause between these signals differed very much: Two participants wanted a long pause of about one minute. The other ones wanted a rather short pause of five or ten seconds. The signal then should be easily perceptible but not too long and obtrusive.

Warning zones: According to the users, the warning zones should be much more intense than the optimal zone. The upper warning zone was generally designed as a vibration sequence repeating every two to ten seconds. The vibration sequence was designed very differently by all participants. Three users described three short impulses. Other sequences were described by only one participant each: one short impulse with a two-second pause, one long impulse with a six-second pause, and two long impulses with a six-second pause. The designs for the lower warning zone didn't reveal any similarities among the participants. Thus, we list them briefly: One 600 milliseconds long impulse every ten seconds, continuing of the vibration pattern of the previous zone (thus, either the optimal pattern or the lower critical pattern), two short impulses every six seconds, four short impulses every six seconds, two long impulses without repetition, and seven short impulses followed by a four-second long pause.

Critical zones: The critical zones were naturally designed as the most intense vibration sequences. To reach this more intense feeling, the participants either used very long vibration impulses of about two to six seconds, a continuous vibration, or a sequence with long impulses. Because during the training the lower critical zone is also reached, e.g. during a break, while the upper critical zone is in general only reached with too intense training, participants rated the higher critical zone as more important. Thus, they generally created a vibration sequence with more vibration and less pauses compared to the feedback for the lower critical zone.

6.2. Every X beats per minute

This design consists of a variable number of zones depending on the width of the acceptable heart rate range. That range is divided into a new zone every *X* beats per minute in both directions. The *X* was defined as five by most participants designing this kind of feedback.

This design was chosen because of its fine granularity and the resulting detailed feedback about the heart rate. Participants expected a good feeling for the heart rate when using this design. The participants started designing with the optimal heart rate as origin. Thus, they created different types of feedback for higher heart rates and lower heart rates instead of e.g. creating a design starting at the very bottom of the acceptable heart rate range. Depending on the value of *X*, this design type might be identical to the *Five Zones* design.

Optimal Zone: Five of six participants wished for no feedback in the optimal zone. Only one participant wanted to have a very infrequent signal as assurance that the system is still working, but could not name a good pause between two signals. The optimal zone is always two times *X* wide because the optimal heart rate is located in the centre and the other zones start at X beats per minute higher and lower.

Higher Zones: The number of zones is variable in this design, so the feedback must be easily scalable. As mentioned before, the optimal heart rate was used as origin by the participants, so this applies separately to the feedback for the higher and lower heart rates. Four participants varied the number of vibration impulses for every step. For example, if the heart rate was *X* beats per minute higher than the optimal heart rate, only one short impulse occurs followed by a long pause. If the heart rate was *2X* beats per minute higher than the optimal heart rate, instead of one two short impulses would occur, and so on. The other two participants chose to vary the impulse length instead. For example, at the first step three impulses with the length of 250 milliseconds would occur followed by a short pause of about five seconds. At the second step, also three impulses would occur, but now each impulse would have the length of 500 milliseconds, and so on.

Lower Zones: For the lower heart rates, four participants used their design for the upper heart rates but varied only the pauses or impulse lengths for discriminability. Another one would like to have a linear design for the lower zones and the last one only one lower warning zone like in the *Five Zones* design.

Critical Zones: For heart rates below or above the acceptable limits, all participants wanted to use the same vibration sequence they designed for the lower or higher zones, but use them without a longer pause. For example, if the design were short impulses followed by a pause for the higher/lower zones, continuous short impulses without a longer pause would be used for the critical zones.

6.3. Other designs

The three other designs were only described by two (*Four Zones*) or one participant(s) (*Seven Zones*, *Linear*). Thus, we report them briefly.

The *Four Zones* design is similar to the previously described *Five Zones* design. The difference is that the lower warning zone was not used in the *Four Zones* design. As described before, the participants thought the higher zones were more important. Thus, two of them designed a *Four Zones* design by extending the optimal zone and eliminating the lower warning zone. The *Seven Zones* design is very similar to the *Five Zones* design, but divides the two warning zones into four warning zones. One participant described a *linear* design, which was similar to the *Every X beats per minute* design but used a linear change of impulse or pause lengths.

7. Discussion

The participatory design study revealed five different design types for vibro-tactile heart rate displays. The *Five Zones* and *Every X beats per minute* were created by a majority of six participants each. We expected more interest in a linear design, but many participants wanted to create easy distinguishable vibration patterns, which seems not to be possible when using a linear design. The *Every X beats per minute* design is a good compromise, since it has zones that can be encoded to be distinguishable but is still very detailed. The *Four Zones* and *Seven Zones* designs were only slightly different from the *Five Zones* design and can be rated as a minor variance designed by participants who wanted a little less or a little more feedback. Our participants only seldom used concrete values for vibration and pause lengths. Instead, they used terms like *short* and *long*, which we categorised and used for reporting the designs.

We intentionally limited the design space. In earlier studies we observed varying perceptions among participants of the intensity of the SmartWatch vibration, making that parameter unreliable. Related work had identified rhythm as one of the most distinguishable elements [13]. We therefore chose to use the Sony SmartWatch, an existing and publicly available device that allows temporal patterns. No participant wanted more vibration motors during the study.

An important aspect to discuss is the very broad age range of the participants in our study. At different ages, people have different cognitive abilities and react differently to feedback. Interestingly, we could not identify any difference between older and younger participants on how the feedback was designed. Thus, it does not seem to be useful or necessary to adjust the vibration patterns according to the user's age, but it is useful to adjust the strength or length of the vibrations instead.

8. Deriving Test Patterns

As described before in the participatory design study, the participants created two major designs: *Five Zones* and *Every X beats per minute*. Of course, the designs for the vibration patterns displaying the different zones differed among the participants. Thus, we derived two designs for further evaluation, trying to consider the design paradigms the participants used during the study and create new logical designs.

Five Zones: For the optimal zone, the feedback was described as minimal, so we used one short vibration impulse recurring every minute. The user designs for the warning zones differed substantially. For the upper warning zone, most users wanted to use three short impulses with short pauses in between, repeating every few seconds. For the lower warning zone, most users chose a different count of impulses but generally the same rhythm. Because 250 milliseconds were often used as a short impulse and 500 milliseconds as short pause, we used these values for impulse and pause length in our design. Based on this information, we used three short impulses with short pauses in between, repeating every five seconds for the higher warning zone. For the lower warning zones, only two short impulses were used and the pause between repetitions was raised to ten seconds. For the critical zones, the designs of the participants were less varied. We found that in general, the higher critical zones should have much longer vibration time and only short pauses, while the lower critical zone should use long vibration impulses but longer pauses. Thus, we used a two second-long vibration impulse in the higher critical zone, followed by a 500 millisecond-long pause, repeating continuously. For the lower critical zone, the vibration impulse length was lowered to one second and the pause length raised to two seconds.

Every X Beats Per Minute: For this pattern, most participants wanted to have no feedback in the optimal zone, so we omitted it. Because most users thought a new pattern every five beats per minute would be best, we used this value for X. For the heart rates above the optimal heart rate, most users chose short vibration impulses and short pauses and varied the impulse count in the pattern every X beats per minute. Thus, we used 250 millisecond-long impulses and 200 millisecond-long pauses. The impulses were repeated depending on the heart rate and were then followed by a long pause of five seconds until repetition. For the lower heart rates, this was only slightly altered. The impulse length was raised to 800 milliseconds, and the long pause between the repetitions was raised to ten seconds. For the critical zones, the repetitions were continuous, thus, the long pauses were omitted.

9. Pilot Study

Initially, we planned to compare a very simple and basic vibration pattern, such as that used in common heart rate watches, to one of our newly created feedbacks designs using a within-subjects design in a field study. Our first study revealed two major designs and both feedbacks seemed to be reasonable and usable for further evaluation. However, we decided that using both feedback designs could be too complicated for our study, since participants would then have to learn three different types of feedback in a short time. Thus, we decided to test both of our designs in a short pilot study to see if one design might be preferred or to discover any major issues that would disqualify one design. Five participants, who were colleagues and relatives of the experimenters went running to test both designs. They were always followed by the experimenter. Both designs were explained to them beforehand. During the run, they reported every change in the vibration pattern and also how they interpreted the changes. Afterward they reported which one they liked more and why. The small pilot test showed that both patterns were generally understandable. The *Every X Beats Per Minute* design was described as a little too complex. Thus, three out of five participants preferred the *Five Zones* design. Additionally, the design seemed to be more flexible, since it is much less dependent on the width of the heart rate limits, which can strongly differ among users. We therefore decided to use the *Five Zones* design in the further evaluation.

10. Field Study

To test if the more complex feedback is effective and suitable for users while actually running, we performed a field study, approved by a local ethics committee. The study revealed significantly better assessment and maintenance of the target heart rate while not raising the cognitive workload.

10.1. Apparatus

For both, the pilot study and the field study, we used a Zephyr BioHarness 3 heart rate monitor[5] to measure the heart rate. The heart rate data was received and processed by an Android app running on a Nexus 4 smartphone. The app translated the heart rate into a vibration pattern according to the designs we described before. The heart rate was filtered to avoid confusing feedback due to short-term incorrect measurements by the heart rate sensor. The filter used the average of the last five heart rate measurements, which resulted in a reaction time of the system of not more than five seconds. Only the observers used the app during the study. The app allowed the observers to control which design was used, to record parameters during the run, and to measure the running time. The vibration feedback was played back using a Sony SmartWatch, which we already used in the participatory design study. The devices are depicted in *Figure 3*.

Figure 3. The apparatus: Zephyr BioHarnes 3 (top), Sony SmartWatch (left) and LG Nexus 4 (right).

10.2. Participants

We conducted the study with 20 participants (13m/7f). The age ranged from 19 to 62. The mean age was 30.4 years (SD: 10.69 years). The participants were recruited with public bulletins at the university and sport centres. The participants were paid for their participation. For ethical reasons, we had to exclude participants with cardiovascular diseases from the study.

10.3. Design

The goal of this study was to evaluate the newly created vibration pattern design. We wanted to investigate if the use of the design is appropriate and effective by verifying these hypotheses:

- H_1: Our vibration feedback improves awareness of the heart rate during training.
- H_2: Users can keep a target heart rate better using our feedback.
- H_3: Our feedback raises the cognitive workload (due to the more complex feedback).

[5] http://www.zephyranywhere.com/products/bioharness-3/

The study started with the same questionnaire we used in the first study, asking for demographic data, physical activity, knowledge about heart rate related topics, and experience with heart rate monitors and vibration feedback.

We used a very basic feedback as a control condition, as provided by heart rate monitors available on the market. The feedback was also tactile and created a 650 millisecond-long vibration impulse every 20 seconds when the user reached the outer limit of her/his heart rate zone. Since our study concentrated only on the tactile feedback, no additional visual feedback was used. The order in which the participants used the vibration patterns was counterbalanced for every participant. Thus, 10 participants started with the test condition and 10 participants started with the control condition. For our study, we also needed the optimal training heart rate for the participants. We computed it by the formula:

$$RestingHR + (220 - age - RestingHR) * 0.75$$

by the *Deutscher Turner-Bund*, which gives a good estimation of the training heart rate, as we have seen in prior studies. Still, it is only one of many formulas for computing the optimal heart rate during training [19]. The computation targeted healthy people without medication.

To verify hypothesis H_1, we asked the participants regularly for an estimation of their current heart rate. This way, we were able to get a fair number of measurements per user without the need for them to remember these estimations to report them later. For all measurements, the absolute difference between the estimated and the sensor value was computed to measure the accuracy. We used the average of these differences per participant as comparison value. We used the absolute instead of the relative values because a positive and negative value with the same absolute value may eliminate each other and give the result of a very good estimation on average, even if the estimation was very inaccurate.

To verify hypothesis H_2, we used a very similar technique as described before for hypothesis H_1. We used the actual heart rate and the previously computed optimal heart rate for the training to compute the accuracy with the absolute difference of both values. Again, we used the average of these differences as comparison value.

To verify hypothesis H_3, we used the NASA TLX in the pen/pencil version, which participants filled out after each condition.

We also conducted a short, structured interview after each condition, where the participants rated the feeling of the vibration, the comprehensibility of the vibration pattern, how well they were able to assess their heart rate with the vibration pattern, and if they would like to use the system. The rating was between 1 for very good and 5 for very bad. For each rating we also asked for comments to clarify it. The interview ended with open feedback, where the participants were asked for any other feedback that was not part of the previous questionnaires or interview.

10.4. Procedure

In the beginning, we met the participants at previously communicated locations. The locations had to be designated for runners and closed for normal traffic. The experimenter explained the study to the participant and answered her/his questions. After the participant had no more questions, she/he signed the informed consent. Afterward, the experimenter handed the heart rate sensor with the chest belt to the participant, which she/he attached to her/his body. The participant then got the first questionnaire about demographic data and existing knowledge, which she/he filled out while sitting. During this time, the experimenter observed the heart rate to get an idea about the resting heart rate of the participant if she/he did not know it her-/himself.

After the participant filled out the questionnaire, the experimenter used the observed resting heart rate to calculate the optimal training heart rate for the participant. If the participant knew about her/his resting heart rate or the optimal heart rate for training, the experimenter used these values instead. The heart rate limits were defined as follows: The warning zones were placed 10 beats per minute below and above the optimal heart rate. The critical zones were placed 10 beats per minute above the upper warning zone and below the lower warning zone. For the control condition, only the limits for the critical zones were set. The experimenter explained these limits to the participant and handed the SmartWatch to her/him. Afterward, he demonstrated the first vibration pattern and made sure the participant did understand the different signals and when they occur. The participant her-/himself decided when this demonstration ended and the running was started.

During the run, the experimenter followed the participant using a bike. Every 30 seconds, he asked the participant to estimate the heart rate and recorded that value. One run lasted for eight and a half minutes, to obtain 16 measurements. Afterward, the participant filled out a NASA TLX questionnaire and answered the questions of the experimenter in the interview. This procedure was then repeated with the second condition. In the end, the participant handed back the equipment to the experimenter, we thanked her/him for the participation, and ended the study.

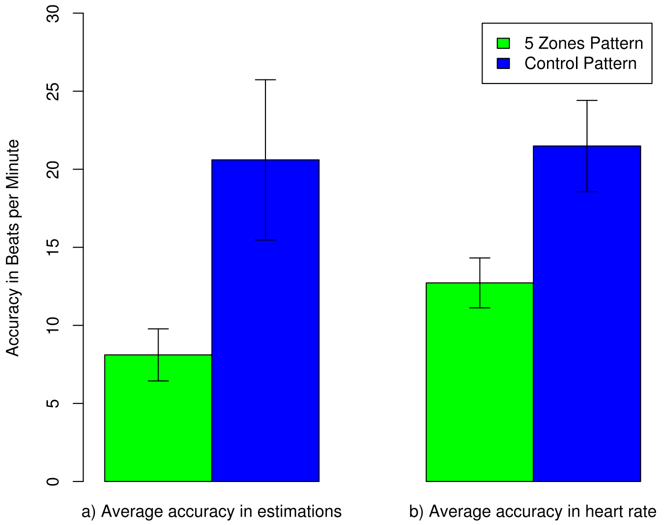

Figure 4. Average accuracy in estimations (a) and in keeping the optimal heart rate (b) compared for both conditions. Lower values are better. Error bars show standard error

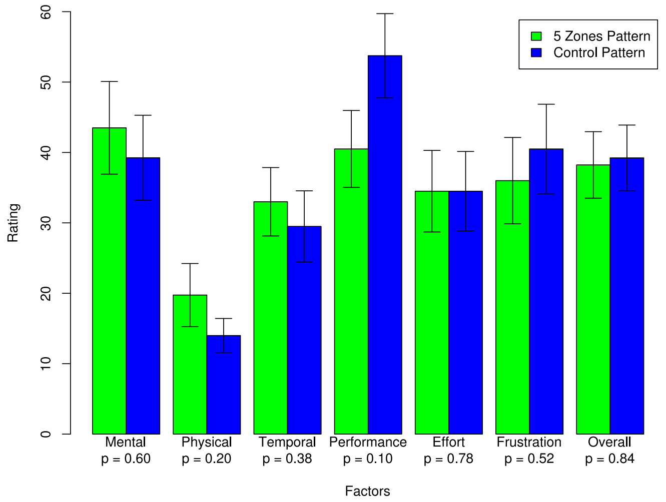

Figure 5. Ratings for all factors in the NASA TLX including the overall rating. Error bars show the standard error. P values were computed using the Wilcoxon signed rank test with continuity correction to check for significant differences.

10.5. Results

The questionnaire about existing knowledge revealed the following information: Two statements on the questionnaire were rated on a 5-point Likert scale: "I am physically active" and "I am able to assess my heart rate". Like before, the ratings on the 5-point Likert scale were mapped to numerical values. A value of 1 represented *Strongly Disagree*, a value of 5 represented *Strongly Agree*. For *physically active*, the median rating was 4.5 (Min: 1.0, Max: 5.0, 1st Qu.: 3.0, 3rd Qu.: 5.0). Thus, our participants generally rated themselves as very physically active. For the assessment of the heart rate, the median rating was 2.5 (Min: 1.0, Max: 5.0, 1st Qu.: 2.0, 3rd Qu.: 3.0). 17 participants reported that they exercise regularly. The median of the frequency of the exercises was 3.0 (Min: 1.5, Max: 5.5, 1st Qu.: 2.0, 3rd Qu.: 4.0) times per week. Eleven participants had used a heart rate monitor before, twelve knew about heart rate zones and their effect on the training, only three knew their optimal heart rate for the training, and five had already used some kind of vibro-tactile feedback before.

To verify hypothesis H_1 ("Our vibration feedback improves the awareness of the heart rate during training"), we compared the average accuracy when estimating the heart rate of the participants in both conditions. The comparison is depicted in *Figure 4a*. The average accuracy of participants when using the *Five Zone* feedback was 8.11 (SD: 7.46) beats per minute. In the control condition, the average accuracy was 20.62 (SD: 22.95) beats per minute. The Shapiro-Wilk normality test showed that both measurements were not normal distributed ($p < 0.001$). Thus, we used the Wilcoxon signed rank test with continuity correction, which showed that the difference between both conditions was significant ($V = 39.5, p < 0.05$). This showed, that our hypothesis H_1 can be accepted.

For hypothesis H_2 ("Users can keep a target heart rate better using our feedback"), we compared the average accuracy during the whole run. This means we calculated the absolute difference between every measured heart rate (one per second) and the target heart rate and used the average of these differences as accuracy. The comparison between both conditions is depicted in *Figure 4b*. The average accuracy of participants when using the *Five Zone* feedback was 12.72 (SD: 7.15) beats per minute. In the control condition, the average accuracy was 21.49 (SD: 13.06) beats per minute. Again, the Shapiro-Wilk normality test showed that both measurements were not normal distributed ($p < 0.01$). The Wilcoxon signed rank test with continuity correction showed that the difference was again significant ($V = 26, p < 0.01$). Thus, our hypothesis H_2 can also be accepted.

To verify hypothesis H_3 ("Our feedback raises the cognitive workload"), we used a NASA TLX in both conditions. In *Figure 5* the ratings for all factors and the overall rating are visualized. The overall rating for the *Five Zone* feedback was 38.23 (SD: 21.12) and 39.23 (SD: 20.84) for the control condition. We used the Shapiro-Wilk test to test for normal distribution for all factors, which declined a normal distribution for at least one measurement series in both conditions. Thus, we used the Wilcoxon signed rank test with continuity correction to check if a significant difference between both conditions existed. No significant difference between both conditions was found. The corresponding p-values are shown in *Figure 5*. Thus, we assume that our hypothesis H_3 can be declined.

For each condition, we performed a small interview with the participants. We also included ratings in the interview for the first three questions from 1 (very good) to 5 (very bad). The perceptibility of the vibration received in both conditions a median rating of 2.0 (Min: 1.0, Max: 5.0, 1st Qu.: 1.0, 3rd Qu.: 2.25). Naturally, the Wilcoxon tests showed no significant difference between both conditions ($V = 23.5$, $p = 0.71$). The comprehensibility of the vibration pattern received a median rating of 2.0 (Min: 1.0, Max: 4.0, 1st Qu.: 2.0, 3rd Qu.: 3.0) for the *Five Zone* pattern and 1.0 (Min: 1.0, Max: 4.0, 1st Qu.: 1.0, 3rd Qu.: 2.0) in the control condition. Thus, while the *Five Zone* pattern still got a good rating, the very simple vibration pattern of the control condition got better ratings. However, the Wilcoxon test showed that the difference was not significant ($V = 83$, $p = 0.19$). Their ability to assess their heart rate received a median rating of 2.0 (Min: 1.0, Max: 5.0, 1st Qu.: 2.0, 3rd Qu.: 2.25) for the *Five Zone pattern* and 3.0 (Min: 2.0, Max: 5.0, 1st Qu.: 2.75, 3rd Qu.: 4.0) in the control condition. The Wilcoxon test showed that this difference was significant ($V = 13$, $p < 0.05$). Thus, the participants felt more able to assess their heart rate when using the *Five Zone* pattern.

Participants generally liked the tactile feedback as heart rate display. Some mentioned they would prefer it over acoustical feedback, because it is less disturbing and cannot be heard by other people. The less distracting character compared to a visual system was also mentioned as a positive. Positive aspects of the *Five Zone* pattern mentioned by the participants were the minimal feedback in the optimal zone, the use of different impulse and pause lengths in the lower and upper zones and the continuous feedback which was thought to be good especially for beginners, who do not have a good feel for their own heart rate. It was also mentioned that a combination with acoustic feedback for the critical zones would be interesting and the ability to use it not only for the heart rate, but e.g. for the pace. Negative aspects were that the vibration was sometimes not easily perceptible, leading to a less well understandable feedback. Especially in the beginning of a run, the concentration needed for the feedback was too much for a few participants. One participant mentioned that the feedback was too complex and therefore hard to use.

A positive aspect of the control condition was the very easy to learn pattern. A positive and negative aspect, depending on the participant, was the minimal feedback. Experienced runners especially were satisfied with less feedback. This is important to note because our target users are heart patients who are not generally experienced runners. Inexperienced runners sometimes stated that the minimal feedback might be sufficient after a learning phase with the more complex feedback. Interestingly, one very experienced runner, who used heart rate monitors regularly in the past and still participates in marathons, also stated that the minimal feedback would be sufficient. However, she/he was very surprised by the feedback given by the *Five Zone* pattern and discovered that her/his heart rate was quite different compared to the past, when she/he observed it with a heart rate monitor. In contrast, inexperienced participants were highly unsatisfied, because they had problems distinguishing the higher limit and lower limit, which were represented by the same signal.

11. Discussion

We were able to show that our hypotheses H_1 and H_2 can be accepted. Our *Five Zone* feedback significantly raised the user's awareness of the heart rate. A visual system can of course deliver more accurate values, but requires the visual attention of the user. Our results show that the accuracy with tactile feedback is also more than sufficient, so that the pure tactile representation is a good alternative for visual systems while keeping the visual sense free for the environment. The control condition was derived from the tactile feedback of commercial heart rate monitors. These systems use tactile feedback to get the attention of the user in certain situations, so she or he does not need to look at the heart rate watch all the time. In our study, we could have used the limits of the optimal zone instead of the outer limits in the control condition. That might have resulted in a higher accuracy in the control condition, but on the other hand might also have reduced the acceptable heart rate range compared to the test condition.

In the interviews, it was stated that more experience would allow the user to use the minimal feedback. On the one hand this seems reasonable, since our presented system gives constant feedback, which should allow users to learn about the behaviour of their heart. On the other hand, our participants rated themselves as very physically active and yet as only average (2.5 of 5) for the assessment of their heart rate without technical help. Still, they showed a worse performance in the control condition and, as described in the results, even a very experienced runner learned about her/his heart rate during our study.

The rejection of hypothesis H_3 was interesting, since the *Five Zone* pattern used a much more complex feedback. Thus, we expected a raise in the cognitive workload, especially because users had just learned the meaning of the feedback before the study. On the other hand, the NASA TLX also considers the performance rating of the participants, which was better with more feedback, but also the comparison of every single factor showed no significant differences. The habituation to the system should lower the cognitive workload even more. When filling out the test, some participants seemed to feel very unsure how to rate the different factors, even if we explained in details what it was about. We can therefore assume an unknown randomness in the answers. However, that always affected both conditions.

For every kind of feedback given to the user, it is important how fast the system can react to changes of the heart rate. In our study, we used the average of the last five heart rate measurements as filtered heart rate measurement. This introduced a short delay of not more than five seconds to the reaction time of the system. While we used heart rate sensors of high value, designers of support systems have to use longer filter intervals if users may use cheaper sensors, which may tend to be less accurate. This problem affects any kind of feedback. However, it plays an important role in tactile feedback, since playing back vibro-tactile patterns also takes time and many changes between different heart rate zones may lead to feedback that is hard to interpret. Thus, we consider it to be very important to carefully choose the filter interval when giving vibro-tactile feedback about the heart rate.

Also, in this study, we had a very broad age range among our participants. Again, we did not see any difficulties recognising the vibration patterns, even by the older participants. The natural difference in cognitive and sensory abilities between younger and older users does not seem to be relevant in our scenario, though. However, because of the less sensitive sense of touch in older people, it might be important to adjust the strength of the vibro-tactile feedback accordingly. In our work, we experienced very different intensities among different smartwatches. Especially newer Android Wear smartwatches seem to have a rather weak vibration strength, which makes them more silent but also harder to perceive, especially during physical activity. Compared to them, the Sony Smartwatch, which we used in both studies, has a rather strong vibration. However, this is a very important aspect for designers of support systems for physical activity. If smartwatches are used in such a system, it is often not possible to control the strength of the vibration. Alternative methods like lengthening the vibration intervals via a user setting should be implemented. Users can also be instructed how to wear their watch. Wearing it tighter and/or on the bottom of the wrist might intensify the sensation of the tactile feedback.

Our presented system relies on a heart rate sensor to determine the heart rate. However, it could be based on more vital parameters, too. BANs (Body Area Networks) can be useful here, as for healthcare in general [20]. The increasing demand of body sensors is expected to lead to low cost sensors [20, 21]. While this offers great opportunities for healthcare by collecting and analysing data [22, 23], it also reveals challenges in securing the private data of the user [24–26].

12. Conclusion

Heart rate monitors are an important utility for observing the intensity of physical training, especially when undergoing rehabilitation from cardiovascular disease. Existing heart rate monitors have certain problems. Visual systems can be distracting, especially if users look at them frequently during training. Alarms can help to reduce but not to avoid this distraction. Further, these systems cannot give constant feedback about the heart rate without the user paying attention to them continuously.

In this paper, we advance understanding of users' needs for a tactile heart rate display through a detailed analysis of related work and the context of use. The most important insight is that existing alarm-like systems are imprecise and insufficient for the users' needs, because they require the user to look on a visual display for further information. This is distracting and limits the overall user experience. Second, our participatory design and pilot study resulted in a zone-based, vibro-tactile interaction concept that communicates the user's heart rate in a more detailed and distinguishable way without requiring visual attention. Finally, we conducted a thorough experiment with 20 participants comparing a traditional alarm-based system with the derived zone-based concept. We found that participants were able to assess and maintain their heart rate significantly better using the zone-based system. We identified no significant differences in cognitive workload.

These promising results can be used for future design of tactile heart rate displays. The significant differences show great potential for the integration of such feedback in fitness apps or even commercial heart rate watches. In future evaluations, the combination with visual and auditory feedback has to be evaluated to assess how and when to use which kind of feedback. Another participatory design study completely focused on the tactile design for five different heart rate zones could allow the design of an even better feedback design alongside our findings.

Our findings may also be used outside the health domain. Whenever a non-visual representation of specific ranges is of interest, our findings are of interest. For example, keeping the speed of a vehicle could be supported with similar feedback or a music student could be supported in maintaining rhythm and tempo.

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